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CAPACITY WITHHOLDING AND STRATEGIC FIRM BEHAVIOR: A AGENT BASED SIMULATION APPROACH TO THE STUDY OF MARKET POWER IN A UNIFORM PRICE AUCTION

This paper applies agent based simulation to UK and Wales electricity market data. The model pairs both bid-price and capacity-withholding computational learning algorithms to strategic agent behavior. The evidence suggests that certain applications of capacity-withholding behavior will generate superior market power to a purely bid-price environment. Additionally non-monotonic price formations are present in two structural variables controlling for market consolidation and decarbonization. The model implies that the strategic behaviors that coincide with marked price differentiation are responsible for these results.

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Introduction

Motivation

The relationship between market structure and market power is a focal point of debate in the study of liberalized electricity markets. The overall aim of this research is to assess the presence of market power and if possible, determine the implications for regulators and policy makers tasked with creating competitive liberalized markets. Previous studies utilizing agent-based simulation modeling have used strategic price bids to examine whether or not imperfect competition may exist wherein a firm may exhibit market power by offering a price in excess of their marginal cost (Bunn, et al., 2010). This thesis adds the strategic withdrawal of capacity to the model. That is, generators may exert market power in one of two ways. First, an agent can increase its offer price above the cost of production. The novel second option allows agents to selectively withhold capacity from the market.

The model uses 2011 market data from the United Kingdom and Wales, a framework which provides an interesting and pragmatic picture of market liberalization. Pragmatic insofar as competition is dominated by six major players along with a competitive fringe. With six major players, the market is on the verge of what may be considered a Cournot environment. Empirically speaking, however, since 1990's the market has appeared to become more competitive and there is little evidence of sustained market manipulation (Wolak & Patrick, 2001). The simulation model is a tool used to evaluate the effect of strategic firm behavior on a uniform price auction. The application does not attempt to predict or recreate price developments; nor does it represent market equilibrium. All of this is done within the confines of actual market participants and realistic measures of generation capacities coupled with historical demand data.

In order to add to the scope and robustness of the analysis, five different variations on strategic agent behavior are tested against permutations of two market structure variables. All 270 simulations are grounded in demand data from 2011. The strategic behavior settings compare the relative effectiveness of capacity withholding strategies to that of a price offer dominated scenario. This evaluation tests the models ability to cope with differentiated strategic behavior. As long as the behavior is empirically relevant, the addition of the capacity alternative will improve the functionality of the model. A qualitative analysis of the results confirms the applicability of certain capacity behavior settings with pertinent implications for policy makers as well as researchers using capacity withholding in agent based simulation. The paper begins with a brief review of uniform price auctions and liberalized electricity markets before delving into an overview of

the model. Finally, an investigation of the simulation data details the significant results and outlines any failures of the model.

Liberalized electricity markets

Goals and reasons for liberalization

Liberalization of electricity markets is often used as an umbrella term to describe intervention aimed to increase the competitiveness of the market. The actual form of the intervention can differ depending on the type of policy measure. To simplify this picture, consider the antithesis of a liberalized or reformed market where all facets of the market are controlled by a vertically integrated government-owned monopoly. A policy measure is considered to be liberalizing if it moves the structure of the market away from a government owned monopoly. In short, the motivation to reform the market is to ultimately serve society in the most cost-efficient manner. Furthermore, this should be realized “by relying on competitive wholesale markets for power to provide better incentives for controlling construction and operating costs of new and existing generating capacity, to encourage innovation in power supply technologies, to provide incentives for network operators to provide appropriate levels of service quality, and to shift the risks of technology choice, construction cost and operating ‘mistakes’ to suppliers and away from consumers” (Joskow, 2008). Figure I provides general classifications of market reform.

Restructuring is a broad term, referring to attempts to reorganize the roles of the market players, the regulator and/or redefine the rules of the game, but not necessarily "deregulate" the market. For example, when California restructured its market, it "deregulated" its wholesale market by lifting nearly all restrictions to how wholesale prices could be set by generators, but kept its retail market fully "regulated," in this case capped. Many problems ensued.

Liberalization is synonymous with restructuring. It refers to attempts to introduce competition in some or all segments of the market, and remove barriers to trade and exchange. The European Union, for example, refers to its efforts under this umbrella term.

Privatization generally refers to selling government-owned assets to the private sector, as was done in Victoria, Australia, with former SECV, in Italy with ENEL, and is being done in France with EdF and GdF. It must be noted that one can liberalize the market without necessarily privatizing the industry, as has successfully been done in Norway and in New South Wales, Australia.

Corporatization generally refers to attempts to make state-owned enterprises (SOEs) look, act, and behave as if they were for-profit, private entities. In this case, a SOE is made into a corporation with the government treasury as the single shareholder. For example, former SOEs in New South Wales, Australia, have been corporatized. They vigorously compete with one another, while all belonging to the same, single shareholder, namely the Government of NSW.

Deregulation is essentially a misnomer. No electricity market has been (or, in fact, can be) fully deregulated. Experience suggests that even well-functioning competitive markets need a regulator, or at a minimum, a market monitoring and anti-cartel authority⁸. Until recently, Germany was the only major country attempting to go without a regulator but with an anti-cartel office monitoring the behavior of market participants.

Figure I (Sioshansi, 2006)

As Sioshansi (2006) suggests, electricity market reform can occur through a number of different changes in market structure. Underlying these disparate reforms, however, is the intent to increase economic efficiency through introduction of market forces. In short, the introduction of free market forces will increase competition and lead to more efficient allocation of resources in the industry. In a perfectly competitive market, production facilities are compensated based on their marginal cost of production. Most liberalized markets utilize what is known as a uniform price auction to set spot prices. The efficiency of the auction is undermined when suppliers are able to exercise market power and achieve prices above their marginal cost. There are two strategies a supplier can employ to distort the market and generate abnormal returns (Wolak & Patrick, 2001). First, the agent can offer a price higher than their marginal cost. Second, the supplier can withhold capacity from the auction in order to force a higher intersection of supply and demand. This is achieved by shifting production to more costly facilities.

In a government-owned monopoly, one entity controls all facets of electricity production from generation all the way to the end consumer. The overriding theme of reform has been to increase competition at one or several points in the electricity industry. The introduction of competition creates a more efficient allocation of capital and encourages innovation in the production process. The long term

benefits to society include prices that truthfully represent the cost of production, an increase in quality of service, and the transversal of risk associated with production from the consumer to the producer (Joskow, 2008). The UK and Wales power sector is considered one of the earliest examples electricity market liberalization, and over the past 20 years, numerous countries have followed suit. Some countries such as Canada and the US have engaged in liberalization separate regions within the country. Others have opted to create international markets as we see in the Nordic power market.

The merit order stack

The most identifiable feature of liberalized electricity markets is almost certainly the mechanism used to clear the demand for electricity with the generators or suppliers. The term pool or auction is often used to describe this mechanism. In the pool, suppliers make bids that indicate the amount of a commodity they are willing to produce at a certain price level. The offers are submitted at a predetermined time before dispatch is to occur. The bidders may make several bids at different price levels. These offers are then stacked from least to most expensive. This ordering creates the merit order stack. Figure II provides a formatted representation of a merit order stack using data from the model. In this example, every agent offers its cost of production which is determined by the technology used in generation.

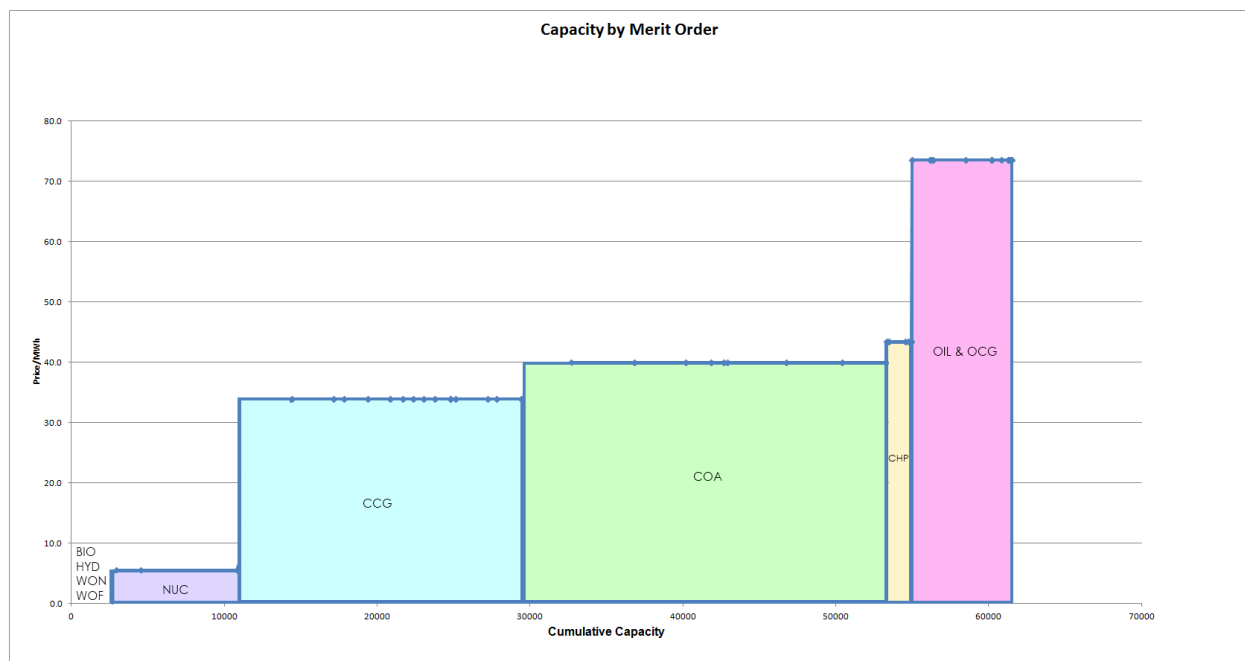


Figure II

The merit order crosses zero at a positive capacity because offshore wind, onshore wind, hydro, and bio (WOF, WON, HYD, and BIO respectively) technologies are assumed to have a negative cost of generation due to government subsidies and carbon incentives. The other technologies are stacked in order

of their relative generating cost. Nuclear (NUC), offered at a price of about six pounds per megawatt, is the cheapest followed by natural gas, coal, combined heat and power, and lastly oil (CCG, COA, CHP, OIL and OCG which is a sub category of oil that has the same production cost). (This nomenclature will be used throughout the paper to denote technology types.)

The price setting mechanism may differ depending on whether or not the pool is a discriminatory price auction or a uniform price auction. In a discriminatory price auction, also known as a first price, each successful bid is compensated based on the price specified in the corresponding offer. A uniform price auction uses a secondary price mechanism where the successful bids all receive the same price based on the highest successful bid. The term successful in this setting indicates a supply bid with a sufficiently low offer to be included in covering demand. Pools may differ in several other ways, including but not limited to: time lag between the initial bids and clearing the market, frequency of the bidding process, amount of information each bidder receives, and number of participants. The type of commodity traded in a pool often dictates the structure of the auction. Electricity pools are particularly interesting because they have to be repeated frequently, there are multiple units of output, it is difficult and impractical to store electricity, and historically market share is concentrated in the hands of a few dominant players (Bower & Bunn, 2001). In power markets, auctions are nearly always paired with bilateral contracts where individual buyers and sellers agree on a quantity and price of delivery beforehand. Furthermore, the price negotiated in these contracts is closely tied to the prices set in the pool.

UK and Wales market structure

Depending on the level of vertical integration, there may be one or several institutional segments in the market. Electricity is first generated by a power plant and then transmitted to the end user via the grid. Generators own the power plants and are responsible for the production of electricity. Transmitters are responsible for delivering electricity to the end customer. This picture may be broken down further depending on the market structure. For example, before liberalization in Britain and Wales, both generation and transmission were controlled by the Central Electricity Generation Board (CEGB). Localized area boards were responsible for distribution to the end users in their geographical segment. Figure III illustrates the industry both before and after liberalization in April 1990.

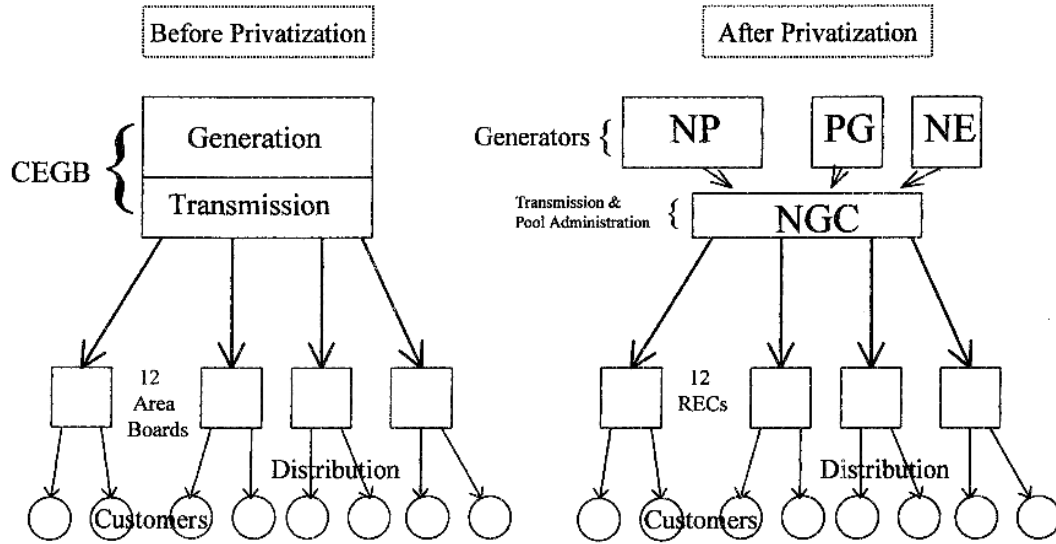


Figure III (Wolfram, 1999)

Reform divided the generation assets of the CEEGB into three companies: National Power (NP), PowerGen (PG), and Nuclear Electric (NE). Transmission assets were vested in the new National Grid Company (NGC) and the 12 Area Boards were privatized and became Regional Electricity Companies (REC). Ensuing divestitures and reforms have further diversified generation to the point that there are currently six main players in generation. Additionally, a competitive fringe has emerged in part due to the decreasing capital requirements of production facilities. As of 2011, the six main players accounted for roughly 70% of total capacity installed in the market. These companies include British Gas which is owned by Centrica, E.ON UK (formerly Powergen), npower which is owned by RWE AG, EDF Energy, Scottish and Southern Energy, and Scottish Power. For the purpose of the model these names have been abbreviated as CEN, EON, RWE, EDF, SSE, and SCP respectively. As Figure IV shows, in terms of UK and Wales market share the big six companies are comparable in size.

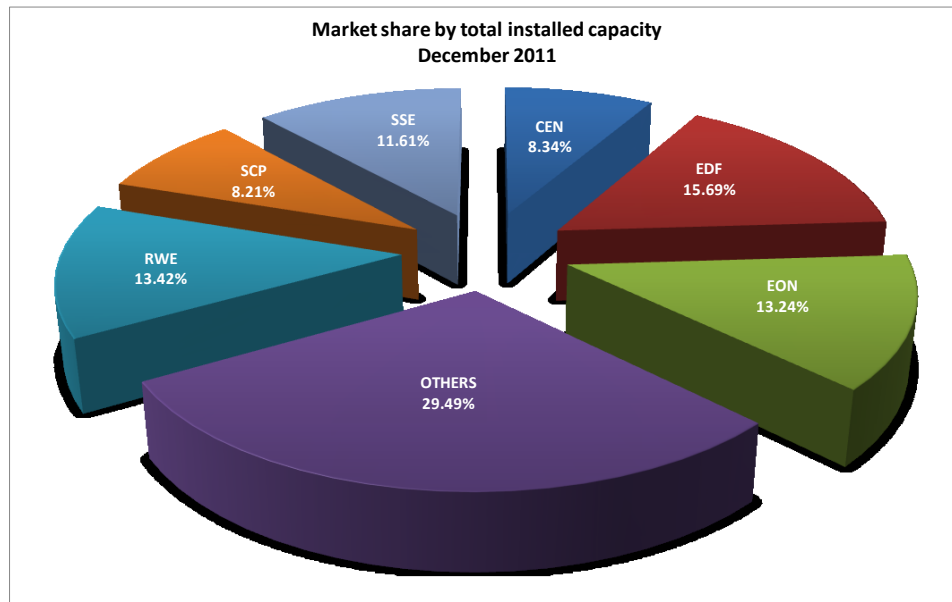


Figure IV

Literature review

Researchers frequently use agent-based simulation to explore the impact of autonomous agent behavior on a system. The model used in this research is adopted from an earlier work designed to explore strategic behavior in liberalized electricity markets. The first publication to feature the model tests whether a discriminator or uniform price auction leads to a more efficient multiunit auction mechanism (Bower & Bunn, 2001). In this study, bidding is also conducted on both a daily and hourly basis to test the effect of the frequency on efficiency. Bower and Bunn (2001) showed that the auction mechanism has a significant impact on market prices with uniform price auctions generating lower prices relative to discriminatory price auctions. These results may be explained by the fact that the model assumes no bid price or market prices are distributed to the actors. Therefore, in a discriminatory auction, large actors with diversified production facilities gradually generate more information about the market due to the greater feedback they get from the success or failure from their own offer. In contrast, in a uniform market every successful bidder receives the same price, thereby limited the disparity in information dispersal. Cognizant of these results, the simulations carried out in this research rely on a uniform price market structure with an hourly price setting. By conducting the auction on an hourly basis, fewer iterations are needed in order to identify market power. The market power mitigating effect of uniform price auctions compared to discriminatory price auctions allows for the assumption that if market power is present in the current market setting, it would also be evident in a discriminatory auction.

The model has also been applied to the Korean electricity market (Bunn, et al., 2010). Specifically, agent-based simulation was used to investigate the relationship between vertical integration and market power. In this study, Bunn (2010) found that, contrary to expectations, the generator with the largest market share does not have the most market power. That is, vertical integration may have a mitigating effect on market power. While they underscore the delicacy of the interaction this behavior has on the market, the authors suggest that these surprising results may be due to the fact that integrated energy companies are less likely to increase wholesale prices and/or operate at lower utilization levels because they are responsible for their own retail obligations. These findings build upon earlier simulation work by Ahn and Niemeyer (2007). Unlike Bunn (2010), this study uses capacity withholding strategies in a Cournot-based model to test market power in the Korean electricity market. The model identifies a strong presence of market power for certain firms exercising capacity withholding strategies.

The model used in this study is an extension Bunn (2001), but includes capacity withholding strategic behavior using the same rationale as Ahn and Niemeyer (2007). In this application an individual plant's offer is dictated by one of three mutually exclusive alternatives. If the company that owns the plant is

not strategic, the plant will always offer its marginal cost. Labeling the plant's parent company as a strategic agent allows the generator to behave either strategically on price or on capacity. Strategic behavior is exogenous to the model. Any company can be set as strategic or non-strategic. Whether a plant owned by a strategic company uses price or capacity behavior depends on the technology it uses for generation. Which technologies are governed by price versus capacity is also exogenous to the model and set before simulation begins. A structure where some operators choose to withhold capacity while others play on price is more flexible and may provide a more empirically accurate picture.

von der Fehr and Harbord (1993) were among the first to use a model with bid-based price increase to address bid behavior of generators in UK and Wales. The model predicts above marginal cost pricing. They show that merit order data is consistent with the bid-curve predicted by their model. Ensuing work by Green (1994) compares generators bids to their marginal cost. He concludes that the offers appear to be consistent with the supply function approach indicating no systematic manipulation. Beyond agent based simulation, Green (2004) compared capacity payments to the avoidable cost of peak power station. Using available UK and Wales market data he found that generators have generally made capacity available in a competitive manner and offered it as long as profits exceed avoidable costs. He further suggested that Cournot models (where firms set quantities) are prone to overstate market prices, and that models where firms instead set prices are likely to give better results. The current research adds to the field of agent based simulation in two ways: by pairing Bunn's model with idealized data from UK and Wales, we attempt to answer, a) what are the capabilities of mixed-strategy agent based modeling in a non-Cournot environment, and b) how does mixed-strategy behavior compare to a purely bid-based price increase setting. Furthermore, results from the model are tested for implications regarding UK and Wales as well as other empirical power markets.

Strategic firm behavior

Market structure and market power

Market power is present if an otherwise efficient market is disrupted by a participant able to exploit its position for material gain. This definition can be applied to a broad set of industries including the power sector. Finding and diagnosing market power in power industry requires a unique set of tools due to the nature of electricity itself. Importantly, as a commodity, electricity cannot be efficiently stored and therefore the receipt of the product is concurrent with its generation. There are a few exceptions to this property of electricity, for example, pumped storage hydro systems can effectively store energy for later use by creating potential energy. However, such techniques have yet to provide a viable solution to the problem of energy storage. Therefore, in a competitive market there needs to be a mechanism that provides sufficient supply to clear the demand for energy. The solution found in most liberalized markets is a wholesale auction that uses a merit order stack to organize producers by offer price. In a uniform price auction, the price of electricity is found where the demand curve intersects the merit order stack. Since the generators are stacked in ascending order based on their bids, the system-wide price (SMP) represents the offer of the last generator included in production.

Not all electricity is traded in the spot market. Entities responsible for transmission to the end consumer may bypass the spot market through vertical integration or through future contracts. Vertical integration entails investing in generation through purchasing existing assets or building new facilities. By integrating downstream in the production process, the capacity related to that firm is taken out of the open market, reducing the size of the spot market. In the context of electricity generation, a future contract is an agreement between a generator and transmission company where the generator agrees to deliver a certain amount of electricity over a time period at an agreed upon price.

Market power is inherently linked to market structure. Without proper consideration of the ramifications of liberalization, a new market structure may give rise to uncontrollable distortions where one player is able to secure profits above competitive levels. According to Joskow(2008), the emergence of this phenomenon can be generally attributed to one of five factors: "too few competing generating companies, wholesale market design flaws, vertical integration between transmission and generation that creates the incentive and opportunity for exclusionary behavior, excessive reliance on spot markets rather than forward contracts, and limited diffusion of real time prices and associated communications and control technology that facilitates the participation of demand in wholesale spot markets." The ramification of market power is a reduction in competitiveness. Policy makers are often forced to rethink their approach to liberalization.

Such was the case in New Zealand, where regulatory oversight had to be implemented in response problems related to market power. The story of reform in New Zealand illustrates that liberalization is a process, and as of yet there is no quick fix formula that policy makers can apply to the unique characteristics found in each market.

Within the framework of this model there are three important parameters governing the structure of the auction. First, the price setting mechanism may be uniform or discretionary. Second, the timeframe and frequency of the pool can be adjusted. For example, hourly offers versus daily offers. The third distinction is the level of information disbursed to each participant. Bower & Bunn(2001) find that both changing the frequency from daily to hourly and the settlement procedure from uniform to discretionary induce an increase in tacit collusion of the participants. As with earlier work, this model assumes no bid prices or market prices are published. Bower & Bunn (2001) suggest that “under these circumstances small agents are at a clear disadvantage to large agents in a discriminatory auction. Large agents gain an advantage because they have more opportunities to gather, and exploit, scarce market price information simply because they submit more bids and therefore learn more precisely about the current state of the market than in a uniform price auction.”

The parameters governing the structure of an auction are important in setting the stage, but the composition of the market and the features of the actors are the end of the line when it comes to market structure. If the number of generators in an auction were infinite, there could be no market power. No one bid could change the market as a whole. Concentrated structures are more empirically relevant as this hypothetical scenario is impossible and no market is ever perfectly efficient. The composition of the market can also refer to the actual technological assets used in production. For example, the Danish market uses large quantities of wind power compared to the United States where natural gas continues to dominate a large portion of capacity. Market power is not directly linked to technological composition insofar as the auction itself only distinguishes offers by quantity and price. The technology used in generation is instead indirectly linked to market power by the cost of production. In terms of the actors themselves, each entity or company is likely to have a number of productive assets. These features could constrain or promote a generator's ability to manipulate the market.

Strategic alternatives to ensure profits above competitive levels

Firms have two strategic alternatives when it comes to exercising market power. The most straightforward alternative is to offer a price in excess of marginal cost. This may result in a higher price in two possible scenarios related to the generator's position in the merit order: 1) if the generator is the price setter in the merit order stack, increasing the offer will move the intersection of the demand curve, and

subsequently the merit order to the next offer which will be higher unless there is sufficient capacity at the previous SMP, or 2) if a generator previously included in dispatch (i.e., lower in the merit order stack) increases its offer above the system wide price, it will take its capacity out of production at current price levels. Again, if there is not sufficient capacity to cover their exit, prices will move to the next lowest offer in the merit order and the spot price will increase. In both of these scenarios, the new spot price could land on either the new higher offer of the strategic generator, or at the offer of a generator with a price bid above the previous SMP but below the new offer of aforementioned strategic producer. This distinction is important, because if the strategic generator's new offer bumps them out of the dispatching merit order, they will not receive the spot price and their capacity will be dormant.

The alternative to strategic price bidding is the strategic withdrawal of capacity. This strategy involves withholding some portion of capacity from the market in order to bump the intersection of demand higher along the merit order. The generators most suited to this alternative are those that provide “base load,” since they are almost always included in dispatch and often satisfy a significant portion of total capacity. Base load refers to capacity that is lower in the merit order stack and almost always included in dispatch. The significance of the behavior depends on whether or not the withdrawal creates a large enough deficit in the merit order stack such that supply does not fully satisfy demand at the current price level. If these conditions are satisfied, the auction will experience an increase in the system wide price. However, this does not guarantee increasing profits, as the downwards pressure on profits by capacity reduction may outweigh the upwards influence of the higher price. Consider for example a nuclear facility that needs to withhold 90% of its capacity in order to achieve a 5% increase in price. In almost any scenario, this would lead to a reduction in profits for the generator.

It is important to note that this interaction depends on the cost structure of production. To illustrate this point, consider the unlikely situation wherein a plant has a marginal cost equal to the current spot price, and additionally has no fixed costs (therefore dormant capacity will not have negative financial repercussions). With this cost structure, the plant is impartial as to whether they dispatch or not, since neither scenario results in profit. If withholding capacity leads to higher prices, the optimal strategic response will always be to withdraw capacity since the alternative is zero profit. This extreme situation contradicts the earlier example of the nuclear facility by creating an instance where a 90% reduction in capacity would lead to higher profits. Realistically speaking, however, all generator plants face fixed costs and most types of plants are not able to stop or scale production without costs. Therefore, the flexibility of production and the cost profit depends heavily on the type of technology employed by providers; it follows that certain plants are more suited to this behavior.

The picture becomes more complex when considering firms with numerous generating facilities; most large energy firms own several production facilities. Naturally, overall profit to the firm is given as a summation each individual plant, but strategic behavior is conducted at a plant level since each plant has a disparate place in the merit order stack. The firm does not bundle together the plants into one offer and each strategic plant chooses a price and capacity bid in order to increase overall firm profit. The effect of each individual plant's strategic behavior has ramifications for the other plants as well. The auction gives a uniform price to all participants included in dispatch. Therefore, strategic behavior by one plant may induce lower profit for its isolated operations while simultaneously increasing profits to the other plants owned by the firm. The simulator used in this research is able to capture this interaction, which is especially important when capacity play is included.

Technologies suited for strategic behavior

A plant's strategic behavior capabilities and the corresponding payoff depend mainly on where the plant is in the merit order stack. If the plant provides base load the operator may not want to risk being excluded from the dispatching merit order for any part of the day. This is especially true for inflexible technologies where there is a significant cost or lag in starting and or stopping generation. These base load operators are therefore relatively unlikely to pursue price bidding strategic behavior. On the other hand, base load technologies such as nuclear tend to comprise a significant portion of the overall capacity dispatched over a given period. By systematically withholding capacity a large plant may create a gap between supply and demand at the current price levels and force the market to a new higher equilibrium. Technologies best suited to play on price are those that produce at the margin. These plants are price setters and may have significant influence over market clearing equilibrium. Likewise, facilities with a high marginal cost are able to take advantage of scarcity situations and offer prices far above the cost of production.

Due to the characteristics of base load technologies, this research allows for capacity play for nuclear and wind facilities. For these plants, the ability to play strategically also depends on the flexibility of the particular technology. For example, it is easier for a wind facility to withhold small increments of production, whereas a nuclear plant may have fewer generating units, resulting in less flexibility. Despite these differences, the model generalizes capacity withholding strategy as a percentage withdrawn compared to available capacity. This allows the learning algorithms to dictate firm behavior without penalizing companies for seeking optimal strategies.

Risks faced by the firms

A company involved in electricity generation is subject to a number of risks, many of which are beyond the scope of this analysis. The previous two sections have already applied the concept of risk to strategic firm behavior. To summarize, increasing a price offer puts a firm at the direct risk of not being included in production. In a capacity withdrawal situation, the firm risks not being able to sufficiently increase prices to compensate for the now dormant capacity. The potential downside of these strategic behaviors becomes less predictable when considering a company with several productive assets or a market where the offers of other participants are unknown and may vary. The following discussion touches upon the inherent risks associated with the technologies used in production and then looks at dormancy and price risk.

The risks faced by firms operating in electricity generation are highly dependent on the type of technology used by the firm. For example, offshore wind plants are capital intensive and are subject to the unique climactic risks in that the wind turbines' generative capacity depends on the strength of the wind. On the other hand, gas- and coal based power plants are less capital intensive, but are subject to variations in the price of the commodity they use to operate their plants. Other factors relate to policy considerations, for example, wind turbines currently receive government subsidies while carbon-based technologies are facing increasingly harsh regulation. A plant's "levelized" cost of electricity (LCOE) breaks down the cost of energy production into three sections: fuel, operating and maintenance, and capital costs. Figure V provides a maximum and minimum estimation of LCOE for a number of different fuel sources as of 2013.

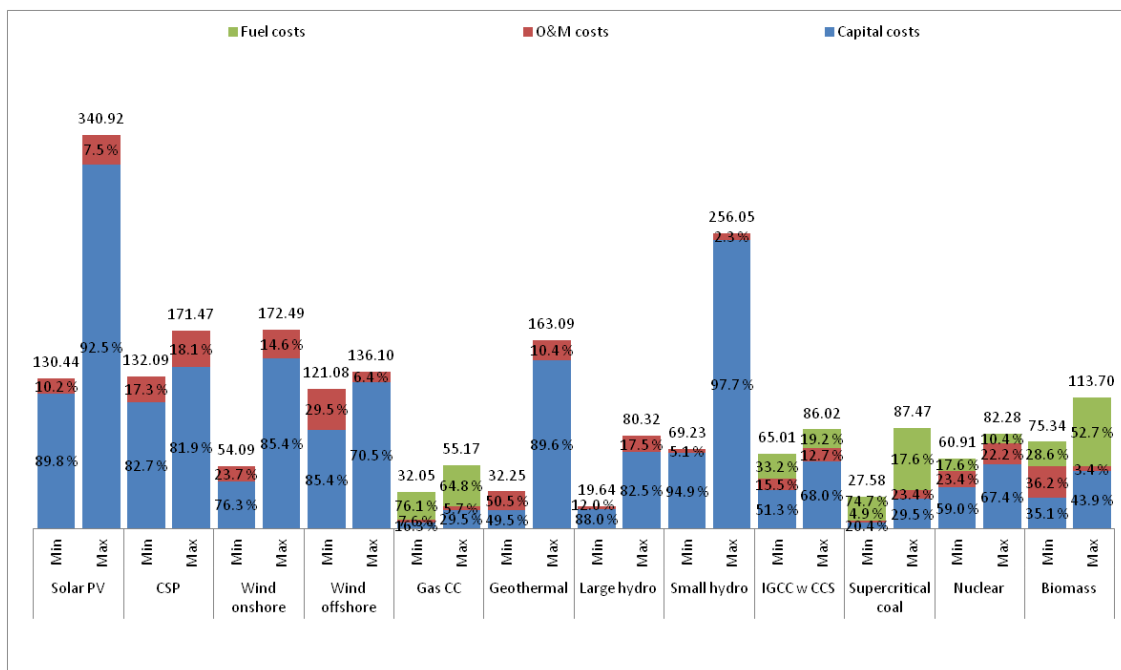


Figure V (Hansen, 2013)

The actual values presented in the diagram are not directly applicable to the model which uses generalized assumptions. Instead it shows how essential technology composition is to the cost of electricity.

As discussed above, several factors converge to set the structure of the merit order stack, and in order to diversify away some of the risks associated with technologies, many firms operate across two or more segments. For example, in Britain, the generator Centrica owns onshore and offshore wind farms, a nuclear power station, a gas fired plant, and they plan to build a biomass facility. The technologies a company invests in determine where in the merit order they are able to provide electricity. Some are more heavily invested in providing base load due to their investments in nuclear facilities, while others operate only in peak periods when incremental capacity is needed.

Besides risks related to production technology, generators try to avoid dormant capacity because this can result in financial outflows. Dormant capacity can be the result of several factors such as overinvestment that leads to overcapacity or an unanticipated shift in demand. Generators are often paid a nominal amount to keep capacity available to the market in order to have a buffer and reduce the risk of blackouts. Still generators need to cover both their capital costs as well as generation costs so dormant capacity can be financially disastrous. This risk requires strong “inter-temporal” decision making given the lag between the decision to invest in a production facility and the time it comes on line. In the simulation model used in this research, unused capacity means the plant is not included in the part of the merit order used to clear demand and the company receives no revenue for their offer, as in the case of a uniform auction.

In a competitive market, the market price is exogenous and no one firm can influence the intersection of supply and demand. As price takers, generators face price risk and a change in price may lead to unacceptable returns. Price risk faced by actors in an imperfect market differs from that of price takers since independent actors may be able to exercise market power. This leads to price risk related to unanticipated changes in price caused by other actors in the market. In Britain, the competitive fringe are price takers whereas the big six companies may be able to distort the market. The risk faced by the competitive fringe is that the major players will distort prices and push them out of the merit order. There is also an inverse upside of this risk where the market power leads to higher prices and in turn increases profits for the fringe. The latter effect is present in the simulation model where prices are strictly above market equilibrium due to the design of the computational learning algorithms. For large players in the market, price risk comes from unanticipated changes in price due to the actions of another major firm. This risk is only present in the absence of collusion. Additionally, the simulation model considers a scenario where each firm optimizes their own profits without entry or exit from the market. The result of this is that

in the simulation, firms are not motivated to "push" one another to bankruptcy in order to secure or increase their presence.

The model

Framework and purpose

The model is designed to simulate a power market which is settled the day before production is required. At the core of the model are two learning algorithms used to test the impact profit maximizing behavior in a variety of conditions. Even though the agents in the model are not collusive, collective market power may occur given tacit collusion between agents. Empirical data is used but the model reflects a stylized and simplified version of reality. It is by no means a predictive tool and results are often unrealistic. Instead it is designed to explore the potential presence of market power. It does so by motivating one or more of the agents to increase profits by distorting the market. The model is run as an excel file. The code is written in visual basic and uses the inputs from the excel file to populate the output section.

In and of itself the model can be used to simulate a multitude of different markets and market conditions. All applications presented in this study are formatted to simulate a uniform price auction. The code reflects each plant putting in an offer in Pounds per megawatt hour (MWh). The code stacks these offers in ordered from least to most expensive to compose the merit order stack. The composition of this stack is done the day before generation is to take place. Once the merit order stack is complete, the model takes hourly demand data and finds the intersection of supply and demand for every hour of the day. Demand is assumed to be inelastic and follows empirical data with peak periods during the day when electricity is most needed. The point at which demand intersects the merit order stack gives the system marginal price (SMP). The plants with offers less than the SMP are scheduled to dispatch. These plants are represented by those to the left of the SMP in the merit order stack. **Figure VI**~~Error! Reference source not found.~~ is a graphic representation of this process using the actual data from the model. Each diamond on the top of the technology stacks represents plants and the black vertical lines indicate hypothetical demand figures.

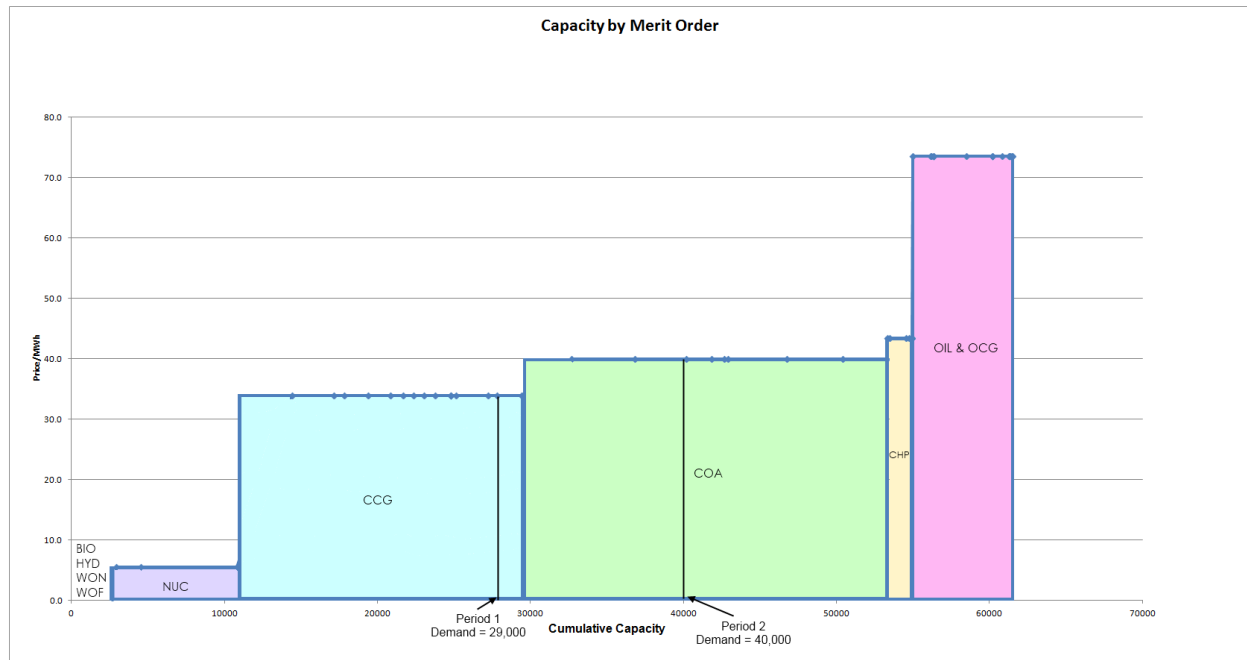


Figure VI

In period 1, the demand intersects the merit order stack at a price of 34 pounds/MWh. Because it intersects the CCG box significantly far to the right, most CCG plants will be included in dispatch along with nuclear, bio, hydro, wind on shore and wind off shore. In the second period, demand is higher which leads to a coal power plant setting the SMP of 40. Plants included in dispatch receive the SMP while those to the right of the market clearing point are not paid. When it comes to strategic behavior, plants base their next offer on companywide daily profit. Total company profit is calculated as the sum of profits earned by plants owned by the company. Each plant's profit is defined endogenously as the difference between marginal cost and the SMP multiplied by the amount dispatched. If the plant is excluded from dispatch, their profits will be zero.

This uniform price auction is at the 'back end' of the electricity market. The model does not forecast any competition or strategic behavior further upstream. This means that retail competition is excluded and demand is considered inelastic. While the model allows for vertical integration, foreclosures, and pumped storage,, these factors are ignored in the simulations. Additionally, the model assumes that no information about the merit order stack is made public. Companies are not able to predict the impact of a course of action until the offer is accepted or rejected.

The base case for all market settings is a scenario where every plant offers its marginal cost. The merit order stack in Figure VI uses this scenario. These simulations are meant to emulate the conditions of a perfectly competitive market. In this market, no plant or company has market power. The model

idealizes this scenario with flat line prices equal to the initial equilibrium of supply and demand. To identify the strength of capacity withholding relative to price strategic behavior, simulations are conducted for all combinations of five behavior settings, six concentration levels, and nine different technological compositions or decarbonization levels.

The agent based computational learning algorithms

The model assumes that companies' behavior is driven by two facets of production: the desired utilization rate and company profits. The desired rate of utilization relates to a level of production each company must exceed. The figure is endogenous to the model. It constrains the decision making process by setting a lower limit for production. If a company is not in compliance, the algorithm will force them to reduce strategic behavior. Empirically, these figures may relate to factors such as legal requirements, preexisting contracts for capacity, and production required to cover fixed costs. This parameter is held at ten percent for all simulations. The intuition for this assumption is that it will allow agents a large degree of leeway before they are forced to act less strategically. The company profit is defined endogenously and calculated on an hourly as well as daily basis. The algorithms use daily profit as a proxy for the company's performance over each trading day. The variable x in the following figure is a randomly generated number between 0 and .15 for the price algorithm. The capacity algorithm uses a random figure between 0 and .2. Granted the company is above its desired utilization level, both algorithms reward and intensify strategic behavior if and only if profits are increasing on the company wide basis.

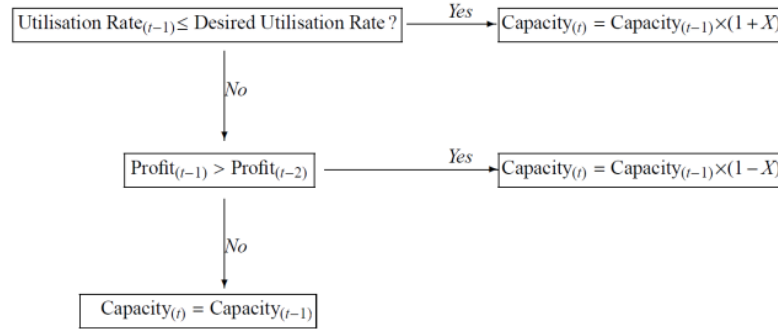


Figure VII - Capacity algorithm

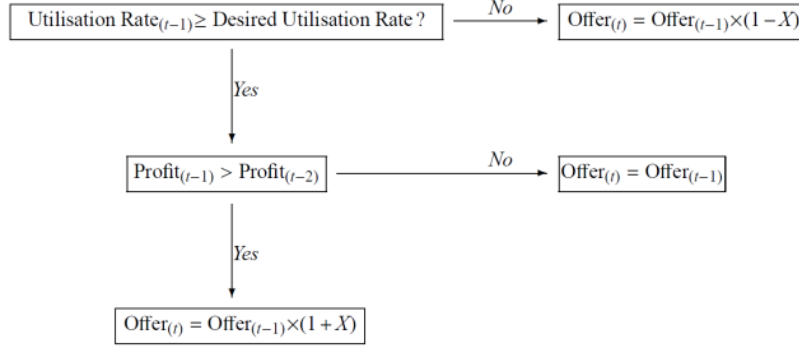


Figure VIII - Price algorithm

Each plant owned by a strategic company will adhere to one of these two algorithms. Note that the model does not allow for any single plant to act strategically on both price and capacity. While the thinking and structure behind the two algorithms are nearly identical, there are some slight differences in their form. If the company as a whole is below its desired utilization rate, a strategic capacity plant will increase its capacity offer by one plus the variable x . Meanwhile, the response of a strategic price plant would be to decrease its price offer. The lower price moves the offer further to the left in the merit order stack, which means that the plant is more likely to be included in dispatch—thus increasing the overall utilization rate of the firm. In this way, strategic price and capacity behaviors are inverses of each other. An increase in the scale of strategic price behavior corresponds to increasing the price bid while an increase in the degree of strategic capacity play means lowering the capacity bid. To reiterate, no firm can be simultaneously strategic on price and capacity. This means a strategic capacity player will always offer its marginal cost while a strategic price player will offer full available capacity.

Strategy and market structure inputs

The model can be applied to any complete set of market data and it allows the user to control for numerous inputs. This study uses UK data from 2011 and fixes assumptions for several of the inputs while focusing on the effect of a few key variables. This section starts by identifying the rationale behind some of the important assumptions. Following this discussion is an overview of the key inputs along with a theoretical justification of their importance, for example, variables are sometimes disregarded or flat lined in order to isolate the impact of strategic behavior on the system wide price. Lastly, attention is given to outputs that provide the foundation of the analysis.

One of the key assumptions of the simulation model is the exclusion of vertical integration, that is, no generators are taken out of the auction due to downstream acquisitions. The competitive fringe is never a strategic player as it is assumed that each entity is a price taker. These “fringe” plants are owned by companies other than the big six and each plant’s bid is always equal to its marginal cost. In order to reduce

the effect of differences in climate and/or other exogenous factors, all simulations are performed during December. Demand varies on an hourly basis but all days in December are assumed to have the same demand. Another important assumption to note is that the marginal cost for different technologies is held constant.

There are three basic classes of inputs that provide the variation in the results. The first variable, strategic behavior, relates to the question of whether a technology is strategic on price or capacity. All plants owned by one of the big six companies are strategic, but whether they are strategic on price or capacity depends on the technology used in production. This decision indicates which learning algorithm will be used for each plant. The five different settings are described in the results section. Practically speaking this distinction is controlled for as a binary variable in the model with 0 relating to strategic price and 1 indicating a capacity withholding strategy. Strategic price play is used as a benchmark of strategic behavior. Subsequent simulations introduce capacity play for either nuclear facilities, wind based generators, or allow strategic capacity play for both technologies.

The second input variable of importance is the level of decarbonization in the market. Altering this input changes the composition of technologies used in generation in favor carbon neutral facilities. Increasing decarbonization increases the share of production for wind based generation. The real available capacity in the market is held constant. Since wind based plants are suited to play on capacity, simulations based on high decarbonization levels indicate a market structure where generation by plants that are strategic in terms of capacity fill a larger portion of the market. The relative share of generation is important for strategic capacity technologies. Functionally speaking, decarbonization is controlled for over five year intervals. Longer time periods means more time for decarbonization to take place. Since demand data is still grounded in 2011, a simulation using decarbonization targets 40 years in the future and reflects a scenario where the projected technology mix 40 years from now is applied to the 2011 market.

The last exogenous variable is the level of consolidation in the market. There are six separate scenarios in which the big six companies gradually merge to become one large entity. The progression of these mergers is as follows: in Big 5 EON buys CEN, in Big 4 SCP buys SSE, in Big 3 EDF buys RWE, in Big 2 SCP buys EDF, in Big 1 only EON is left. These purchases or mergers are sequential and Big 3 implies the mergers in Big 4 and Big 5 have already taken place. The structure of the transaction may also be interpreted as a merger between the two firms instead of an acquisition. The model achieves this flexibility in interpreting market consolidation by using the same algorithms to describe strategic behavior regardless of the organization. Decision making differs between firms due to differences in each company's portfolio. Figure IX and Figure X depict changes in the market structure across the consolidation scenarios

both without any decarbonization and in year 40 when offshore wind power has completely replaced coal production.

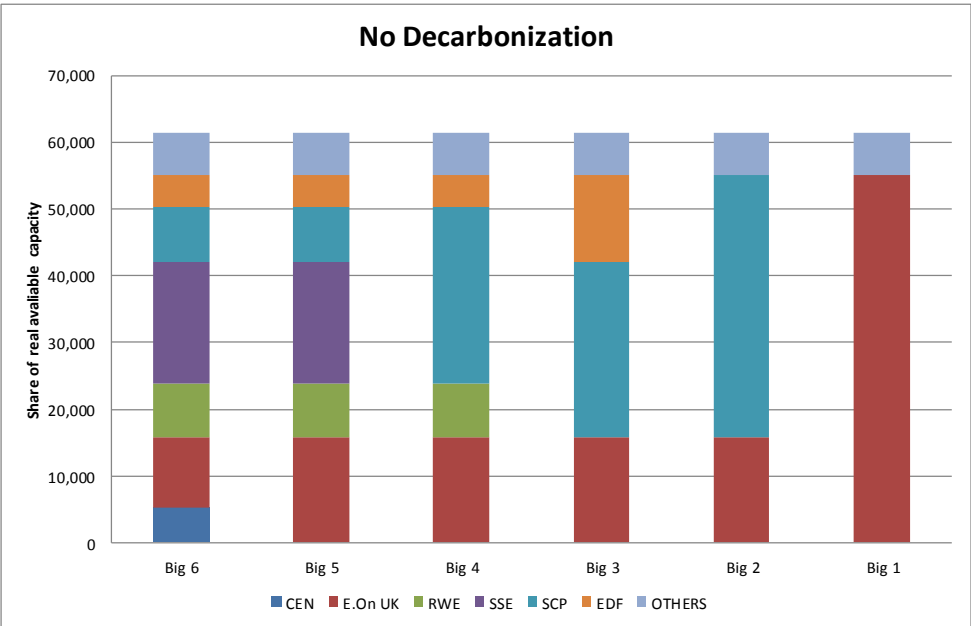


Figure IX

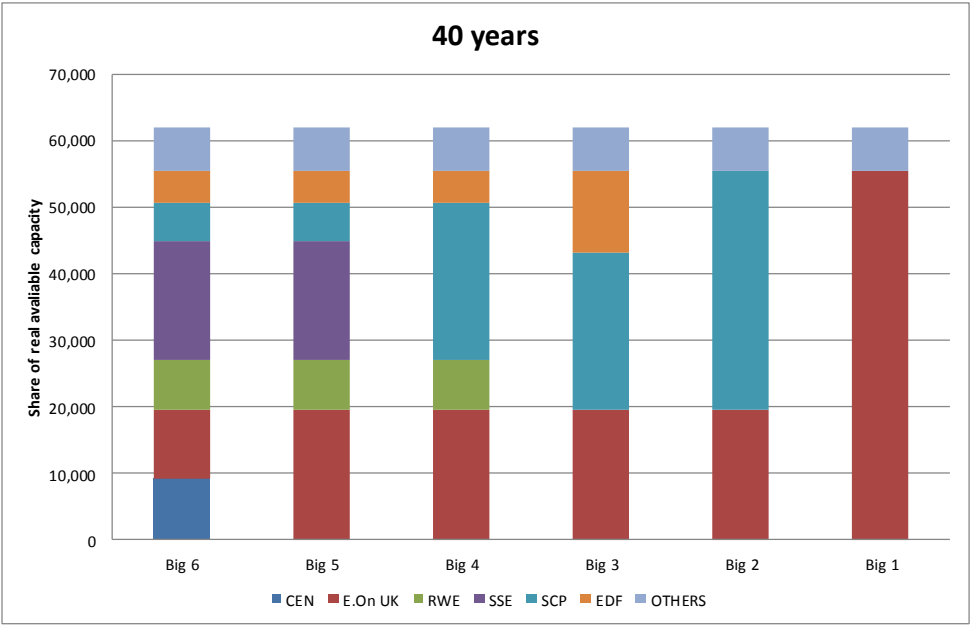


Figure X

The similarity between the two figures indicate that there is little change in market share for any of the big companies in year 40 compared to 2011 levels. This is important because it helps sterilize

distortions between the two inputs. The result highlights the extent of diversification among the large players' productive assets. Since each player owns plants across several technological groups, the increasing share of wind power compared to coal does little to upset the balance of the market. CEN has the most pronounced change in market share, increasing the total real production of its assets a little less than half in year 40. This is because CEN has a large offshore wind facility that the model adds additional capacity to in order to simulate an increase in market share of offshore wind technologies. After CEN is purchased by E.On UK in Big 5, the increase in Centrica's market share is transferred to E.On UK. Since total real available capacity stays stable at around 60,000 megawatts in all market scenarios, CEN's increasing real available production necessitates a corresponding decrease by other market participants. By comparing each company's productive capabilities in the same two decarbonization scenarios, it is evident that RWE is primarily responsible for this corresponding decrease. Figure XI presents another view of the same market structure developments.

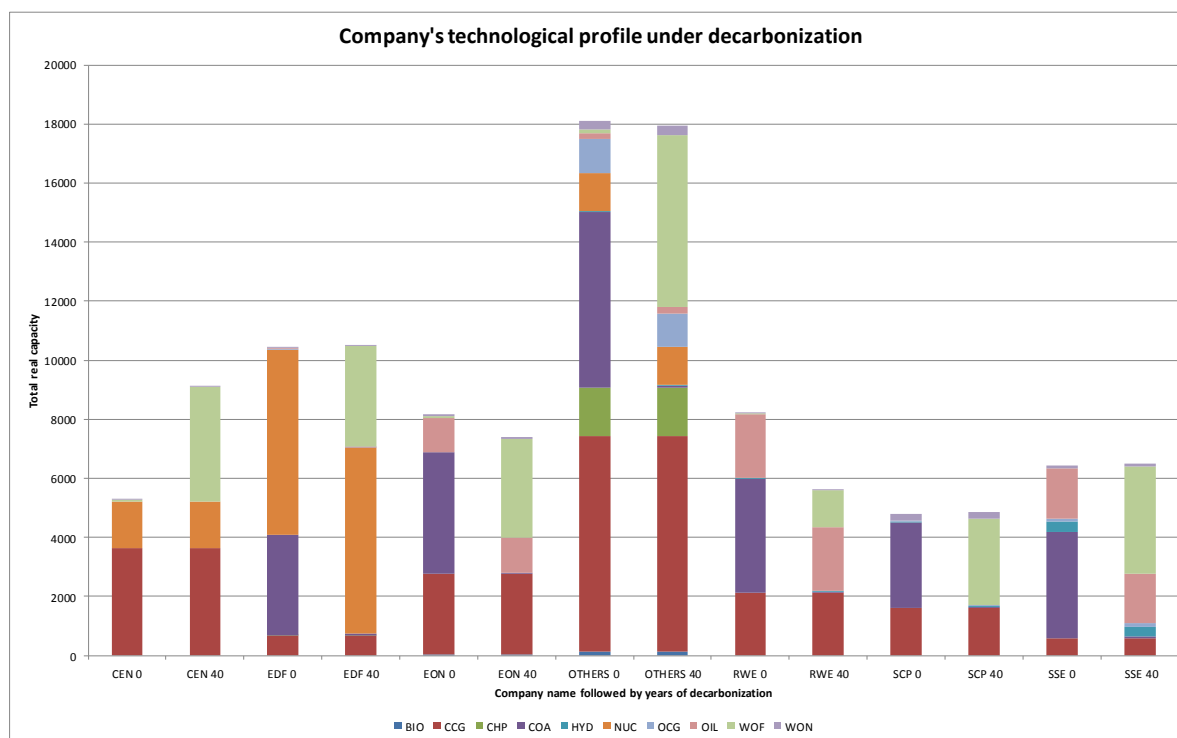


Figure XI

RWE suffers a decrease in real available capacity because as of 2011, the company's assets are primarily coal based and so far they have yet to develop significant offshore wind facilities. This diagram also shows that as expected, other companies such as EDF and SSE offset decreasing coal production by ramping up offshore wind operations. The model assumes that these companies that are comparatively early to move into the market will be able to continue to command a dominant share of offshore wind

production. The code achieves this by allocating increasing offshore wind production to existing facilities. It is difficult to see the existing offshore wind capacity the previous graph because currently wind technologies contribute to a negligible portion of overall real available capacity. Figure XII gives yet another view of the decarbonization process by breaking down total capacity in the market by technology instead of by company.

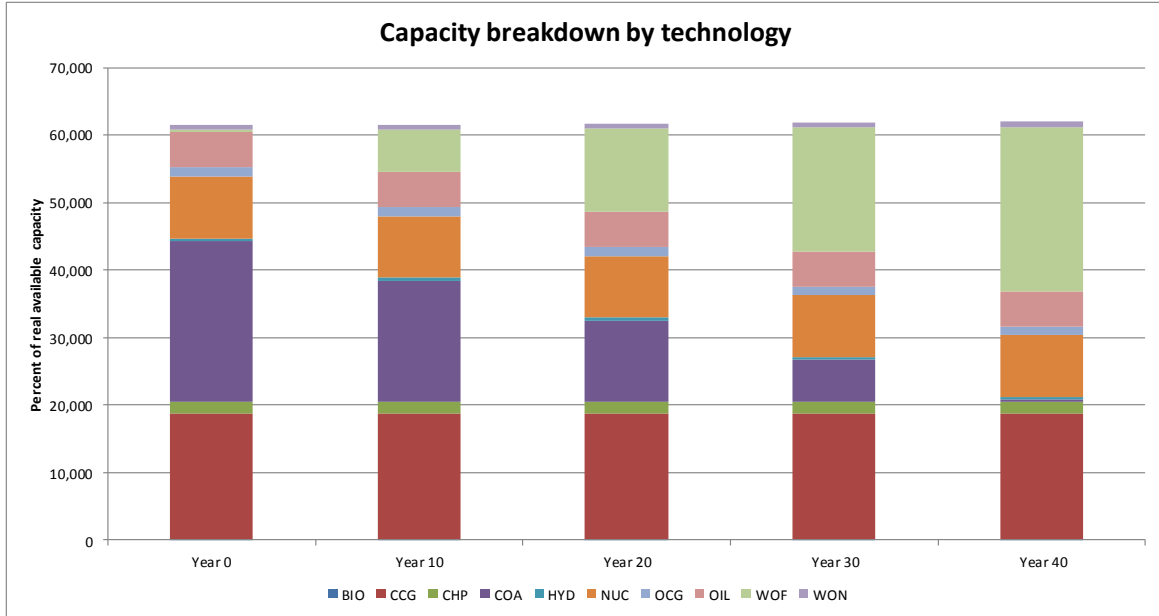


Figure XII

Despite the limited effect of decarbonization on corporate market share, this figure shows that there is a major change in the technological composition of the market. This change will have a multifaceted effect on the model due to the difference between the marginal cost of wind and coal. Each unit of offshore wind production has a marginal cost of negative one hundred due to government subsidies and carbon rights whereas coal plant's marginal cost is forty. This related to a decrease in capacity that would normally produce in peak periods and an increase in base load.

Average daily prices are used as a barometer of manipulation in the model. For example, if a strategic behavior is able to generate an average daily price that is twice as high as competitive levels it is possible to categorically confirm the presence of market power in the model. By itself the average daily price does not indicate either why or how a company is able to manipulate the market. Telling the whole story requires data from the algorithms as well as the merit order stack. Profits may be extracted at a plant level or a firm wide level, while data related to the algorithm is unique to individual plants. When discussing the strategic price algorithm, mark ups (measured as a percentage increase in offer above marginal cost) are used as a proxy indicating where in the algorithm the firm ended up for each iteration. In the same way,

percentage of real available capacity withdrawn is used as a proxy for plants that are strategic on capacity. The relationship between the algorithm and profit data illuminates the decisions made by each plant. Finally, further information on the market as a whole is needed to complete the picture. For example, the price offer and plant name last generator included in the dispatching merit order indicates the intersection of demand and the merit order stack.

Expectations

The impact of one generator's strategic behavior in an otherwise perfectly competitive market is easy to calculate. When numerous strategic actors are added, that prediction becomes more difficult and chaotic. The once isolated firm must now consider both its own impact on the merit order stack as well as the interaction between their behavior and that of other plants. With respect to a firm with numerous facilities, each plant is forced towards a common goal of company profits. However complex these interactions, it is still possible to infer possible patterns the model may show. The computational learning algorithms are designed such that prices will not decrease beyond the initial market clearing price. The algorithms achieve this by resorting to the offer in the previous iteration if profits are not increasing. If profits are strictly decreasing, the plant will continue to offer its marginal cost. This floor price is given by the result of the first iteration where every plant offers their marginal cost. Simulations that operate using higher levels of decarbonization are expected to have different floor prices due to the technology mix in the merit order. This result should be readily visible in the competitive scenario.

As for market concentration the price formation should be straight forward. A larger entity is expected to garner more market power leading to higher average daily prices in more concentrated markets. Bower & Bunn, 2001 find that larger firms have an information advantage in a uniform price auction. The acquisitions will generate large firms who are likely to command stronger market power than the two stand alone entities. The effect of consolidations should be more or less consistent across decarbonization scenarios given the fairly sterilized development in market share.

Back to the discussion of decarbonization, higher offshore wind capacities will probably lead to an improvement in the effectiveness of capacity withholding wind technologies. Additionally market power is expected to decrease with higher levels of decarbonization. The model assumes that technologies with a negative marginal cost will always bid at a price below zero. This assumption is used to prevent the unlikely scenario that a base load operator using the price algorithm will bid its way up to the SMP. In this way decarbonization introduces base load which will always be offered below zero for coal which is competitively priced at forty. As long as wind technology is set to play on price, it will be added to the total non-disruptive capacity in the market. Non-disruptive capacity refers to the output in the market that will

always be offered at competitive levels for both price and capacity. This includes plants that are owned by the competitive fringe since they are never strategic. Figure XIII provides a graphical representation of the merit order composed of only non-disruptive plants in ten year intervals of the decarbonization process. The triangles on the x axis represent the hourly demand levels used in the model.

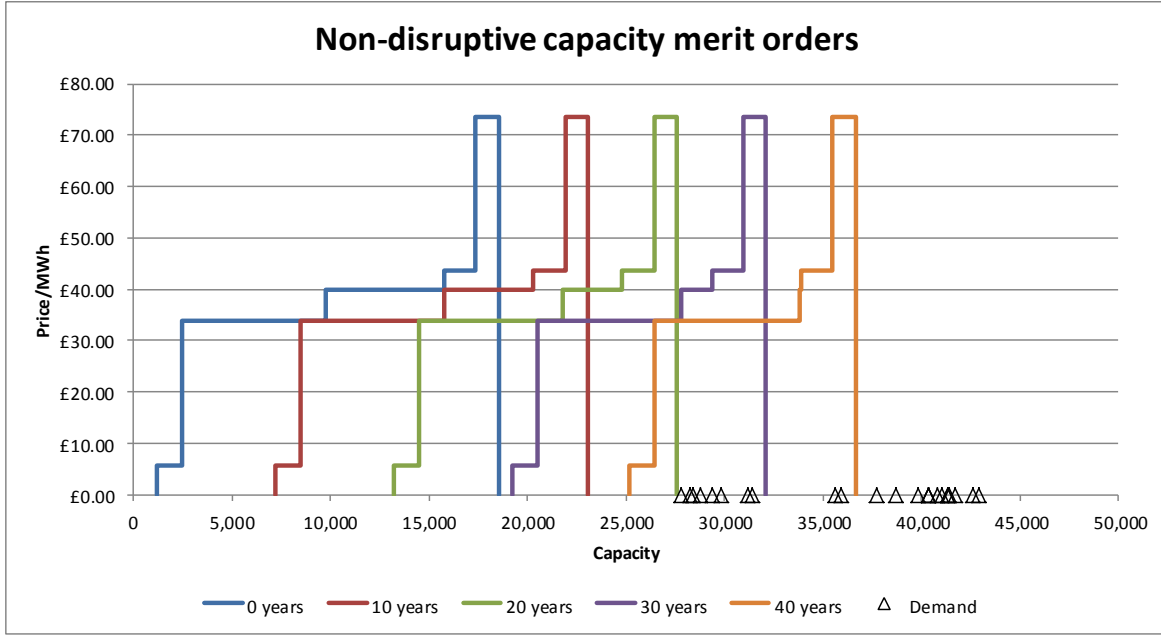


Figure XIII

The strategic agents are therefore loosing capacity that they could use to manipulate the market in exchange for base load which they have to offer competitively unless wind is strategic on capacity. Contrastingly, the competitive fringe does not lose market share under decarbonization but the non-disruptive capacity in the market is strictly increasing because the technologies with a negative marginal cost owned by strategic agents will always be offered at a price below zero. By 40 years the total non-disruptive capacity in the market is capable of satisfying low demand periods. This implies that unless wind plays on capacity market power is expected to decrease with higher levels of decarbonization.

Simulation results

The results are derived from 270 individual simulations run at 200 iterations. Five different strategic behaviors are tested under a combined 54 market settings. These five strategies are assigned the following nomenclature; *Competitive*, *Price*, *Wind*, *Nuclear*, *Wind & Nuclear*. In *Competitive*, each plant offers its marginal cost reflecting an efficient auction with no market power. *Price* refers to behavior dictated solely by the price algorithm and no technology group uses capacity withholding. The *Wind* setting is the same as *Price* except all wind technology plants owned by a strategic company use capacity withholding instead of increasing price offers. *Nuclear* follows the same logic as *Wind* but relate to nuclear plants using capacity withholding rather than wind. Lastly, *Wind & Nuclear* combines the previous two strategies such that plants using either wind or nuclear technology follow the capacity algorithm. Again, no plant can play on both algorithms at the same time; therefore the last three setting tests the efficiency of capacity withholding compared to a price strategy dominated scenario and a base case competitive market.

These strategies are tested in 54 different market settings corresponding to changes in market concentration and decarbonization levels. Market concentration is increased through acquisitions. The process of acquisitions has been described but in order to clarify the results, each level of concentration is named *Big* followed by the number of companies remaining. *Big 6* signifies the present situation with six major companies; *Big 5* allows one acquisition to take place. This continues down to *Big 1* where there is one company left to dominate 70% of the market. The competitive fringe remains unchanged by consolidation. The second exogenous variable, decarbonization, has also already been described at length. Any graph, chart or diagram display the number of years decarbonization followed by years. For example, *40 years*, relates to the most decarbonized market where offshore wind has completely taken over for coal.

Lastly, as for the data points themselves, market power is measured as the average daily price. Average daily price is calculated as the average of the hourly SMP in one day. Each of the 270 numbers in Table 1 is the average daily price as of the last iteration. The results are limited by a price cap of 80 and colored based on their value. Higher prices are red indicating significant market power while lower values are colored blue. This data will provide the basis of proceeding analysis. The results section is broken down into three subsections starting with a comparison of policy mechanisms followed by an analysis of the two market settings: concentration and decarbonization.

Table 1

Strategy	Market Setting									
	Concentration	0 years	5 years	10 years	15 years	20 years	25 years	30 years	35 years	40 years
Competitive	BIG 1	£38.983	£37.967	£37.967	£37.204	£34.663	£33.900	£30.363	£24.467	£21.967
	BIG 2	£38.983	£37.967	£37.967	£37.204	£34.663	£33.900	£30.363	£24.467	£24.467
	BIG 3	£38.983	£37.967	£37.967	£37.204	£34.663	£33.900	£30.363	£24.467	£24.467
	BIG 4	£38.983	£37.967	£37.967	£37.204	£34.663	£33.900	£30.363	£24.467	£24.467
	BIG 5	£38.983	£37.967	£37.967	£37.204	£34.663	£33.900	£30.363	£24.467	£24.467
	BIG 6	£38.983	£37.967	£37.967	£37.204	£34.663	£33.900	£30.363	£24.467	£24.467
Price	BIG 1	£80.000	£80.000	£80.000	£80.000	£80.000	£80.000	£80.000	£57.617	£39.967
	BIG 2	£80.000	£80.000	£80.000	£80.000	£80.000	£80.000	£55.465	£80.000	£37.370
	BIG 3	£80.000	£80.000	£80.000	£80.000	£80.000	£80.000	£80.000	£58.701	£34.959
	BIG 4	£75.793	£80.000	£80.000	£48.016	£37.557	£80.000	£55.523	£42.706	£35.636
	BIG 5	£73.665	£80.000	£80.000	£80.000	£45.871	£60.983	£57.168	£43.428	£35.636
	BIG 6	£66.772	£65.353	£68.486	£70.142	£80.000	£45.829	£40.108	£38.905	£35.339
Wind	BIG 1	£80.000	£40.579	£42.353	£39.322	£38.203	£37.895	£36.779	£26.308	£24.778
	BIG 2	£80.000	£41.704	£42.308	£37.604	£37.868	£38.587	£33.677	£26.776	£24.688
	BIG 3	£80.000	£42.528	£42.848	£38.972	£37.721	£39.927	£36.287	£26.575	£24.697
	BIG 4	£67.313	£44.241	£43.805	£39.834	£37.557	£38.378	£34.025	£26.666	£24.771
	BIG 5	£73.750	£43.149	£39.744	£42.034	£38.711	£38.555	£34.479	£26.817	£24.705
	BIG 6	£66.511	£49.587	£41.365	£41.094	£38.121	£38.241	£35.674	£32.394	£24.891
Nuclear	BIG 1	£80.000	£76.637	£80.000	£80.000	£80.000	£80.000	£80.000	£80.000	£21.485
	BIG 2	£41.122	£41.327	£39.912	£38.971	£80.000	£37.553	£39.737	£80.000	£26.056
	BIG 3	£40.800	£43.297	£52.647	£40.425	£42.027	£37.907	£44.050	£61.524	£24.472
	BIG 4	£80.000	£80.000	£80.000	£42.367	£48.913	£80.000	£61.974	£80.000	£24.478
	BIG 5	£80.000	£67.992	£54.874	£42.362	£56.063	£63.072	£80.000	£80.000	£24.478
	BIG 6	£80.000	£57.604	£42.842	£45.297	£80.000	£80.000	£80.000	£80.000	£24.828
Wind & Nuclear	BIG 1	£80.000	£38.412	£38.117	£37.505	£38.040	£34.612	£33.637	£28.939	£25.007
	BIG 2	£40.196	£42.270	£39.176	£44.777	£37.486	£38.655	£33.870	£27.668	£25.021
	BIG 3	£49.105	£48.908	£42.714	£38.331	£41.231	£38.326	£33.104	£27.221	£25.021
	BIG 4	£44.975	£46.727	£42.549	£40.660	£38.344	£38.671	£40.409	£36.656	£25.051
	BIG 5	£42.262	£50.957	£41.365	£39.577	£38.104	£38.053	£34.058	£33.016	£25.172
	BIG 6	£72.778	£54.409	£41.490	£45.447	£39.838	£38.235	£37.494	£32.746	£25.142

Comparison of policy mechanisms

A cursory glance at the results table shows that market power is most prevalent in *Price* simulations. As for capacity withholding; *Nuclear* clearly generates a greater degree of market power compared to both *Wind* and *Wind & Nuclear*. A granular investigation fractures the hierarchy, forcing a more comprehensive study. Capacity withholding in *Nuclear* can catalyze market power more efficiently than price bidding in certain market settings. Simulations using wind technologies still appear to be ill-suited to play on capacity.

Strategic price behavior

The price algorithm forms the backbone of the model. Capacity behavior is used as a supplementary tool. To reiterate, in *Nuclear* only the plants using nuclear technology use the capacity algorithm while all other strategic facilities play on price. The process of exploiting market power by increasing price offers is unique to the individual simulation. While a detailed description of each instance would insufferable, and may be useless when it understanding the results, to understand how the price algorithm enables agents to exploit the market is quite simple. The competitive fringe is only capable of producing around 18,000 megawatts of capacity, and even at its lowest level demand is almost 28,000 megawatts. During peak periods demand reaches as high as 42,884 megawatts. Strategic companies exploit this gap between supply and demand by increasing the price at which they make their capacity available. What usually happens is that gas technologies which have a production cost of 34 pounds/megawatt are the first to realize their position. Strategic gas plants push prices up to the price of coal at 40 pounds/megawatt. Prices usually stall somewhat until the coal technology sufficiently clears out the capacity at this price and further increases prices. The model stalls because by increasing its offer, a plant may exclude itself from

dispatch if there is still capacity at a lower price level. Several plants may try to be the leader before other strategic plants are sufficiently motivated to join them by increasing their own offer. The process is more complex in the model due to the daily demand variation and by an agent's inability to predict how other plants' strategic behavior will affect the merit order. Several plants may be able to influence the SMP depending on where they are compared to demand. Even with 40,000 megawatts of non-disruptive capacity (capacity that will always be provided at the same cost), a strategic plant can increase prices during the few hours that demand is higher than 40,000 and the average daily price will increase.

The only difference between *Price* the capacity simulations is the behavior of a few base load operators. There are two distinct advantages of allowing base load play on price rather than capacity. First, the base load capacity can increase the price at which it offers its capacity which could provide the necessary push to clear capacity levels out. Initially increasing price bids for base load does nothing to the market price given its low position in the merit order stack. This factor becomes important if and when more expensive capacity has limited market power. Base load facilities are often large and have high operating profit margins. This makes it is costly for them to be excluded from dispatch. These facilities are seldom the forerunner setting the SMP in a simulation, but again because of their size it is more likely that increasing an offer will force higher prices without bumping the agent out of dispatch. This is especially true of low demand hours.

The second advantage of having base load facilities play on price is a function of the interdependence of generators owned by the same company. This feature of the model is a recurring motif. Aligning two plants with a consolidated profit has a multifaceted effect on market power, but capacity withholding is more susceptible to the market power limiting effects of intercompany profit distortions. If the behavior of one plant decreases the profitability of the company as a whole, other plants owned by the same company will also limit their strategic behavior. The profit contribution of a base load plant is typically quite significant. An unprofitable action on the part of the base load operator will constrain the behavior other plants. This proves to be problematic—especially for capacity withholding—due to the profit tradeoffs inherent to the each algorithm. Any potential movement in prices always has to be measured against the drawback of less dispatch. The price algorithm need not exclude any of the facilities capacity from dispatch. In contrast, the benefits of strategic capacity withdrawal will always coincide with some decrease in profits for the withholding plant. With a low starting offer, base load capacity using the price algorithm is unlikely to be excluded from any point in dispatch unless its markup becomes significant. Decreasing the same plant's capacity offer will by definition exclude some of its capacity from dispatch. This issue is accentuated when allowing wind capacity play; this will be discussed below.

Nuclear capacity withholding

Of the three capacity strategies, *Nuclear* consistently leads to more market power. Additionally, *Nuclear* is able to deliver higher prices than *Price* in numerous market settings. The only difference between *Nuclear* and *Price* is the strategic behavior of two facilities that switch from the price to the capacity algorithm. Therefore, the decision making process of these facilities is decisive in determining the differences between the two strategies.

Capacity withdrawal has two distinct advantages over price offers. First, in a market with large differences in the merit order stack's price intervals, the increase in the SMP as a result of behavior will be greater than if the plant currently setting the SMP marginally increased its price offer. Second, capacity withdrawal is an effective means of promoting market power in other strategic plants. It is unlikely a base load facility will ever price itself above the SMP. In a market inundated with capacity, strategic agents around the SMP may need some excess capacity removed before they gain any market power. Capacity withdrawal is important in this model because gas and coal capacity are unable to exert any market power if there is a sufficient buffer provided left of them in the merit order. The buffer may be provided by the competitive fringe or created by the rightwards shift in the merit order caused by decarbonization. For example *Big 6 - 4* simulations yield strictly higher prices for *Nuclear* compared to *Price* in 0 years. The merit order graphs in Figure XIV help illustrate these results. The purple cross sections indicate the position of EDF's nuclear facility.

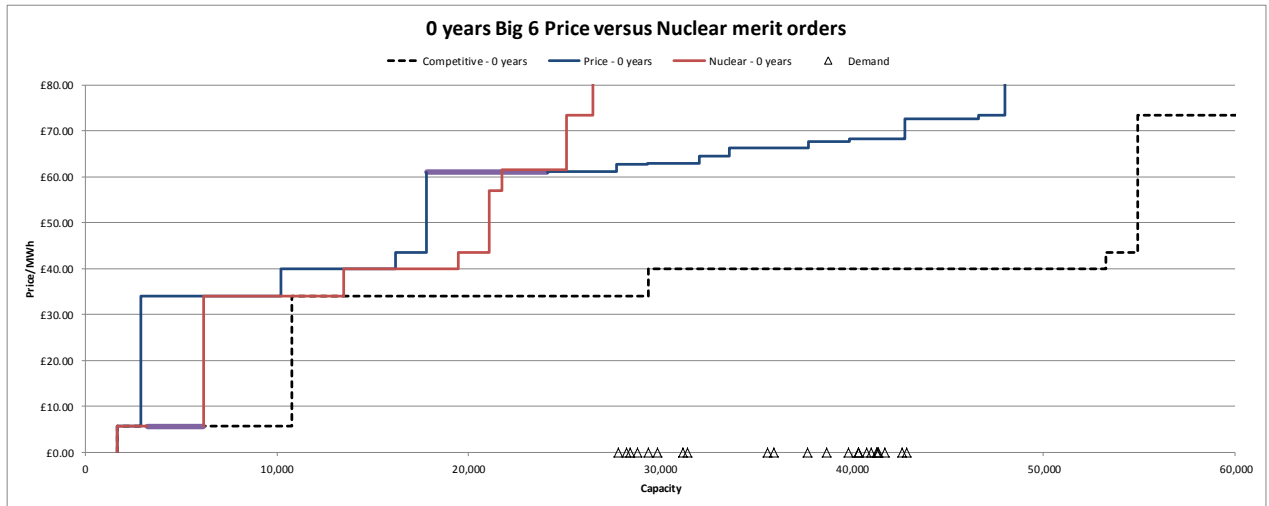


Figure XIV

The two strategic nuclear facilities have a marginal cost of 5.6 pounds. EDF's plant is capable of producing 6,300 megawatts and the smaller nuclear facility run by EON in *Big 5* can generate 1,600

megawatts. In *0 years Price*, checking the offers for both of the nuclear plants, the model shows that both EDF and EON were unwilling to offer a price bid above the SMP. In Figure XIV, this information is embedded in the large purple flat cross section just above 60 pounds. Tracing this section down to the x axis, it is clear that the EDF's nuclear facility is unwilling to exclude itself from dispatch during any hour of the day. Because these nuclear plants are always available; in *0 years* the total available capacity offered by technologies with a negative marginal cost, plus the capacity offered by the competitive fringe at a price of 40 or below, plus the two nuclear facilities confirmed to provide base load comes to approximately 24,000. Adding the competitive fringe's more expensive technologies increases the total to almost 29,000 megawatts offered at a level below 74 pounds. Demand fluctuates between 27,800 – 42,900 MWh on a daily basis so peak periods still require some production by strategic agents. RWE, SCP, and SSE do not have significant base load in this market setting rely heavily on their gas and coal facilities for profits. Adding these facilities to the mix satisfies even peak demand hours.

Nuclear is capable of diverging for these same market conditions due to the incremental push of withholding a small amount of nuclear capacity to lower the 29,000 figure. In Figure XIV the shortened purple cross section at a price of 5.6 confirms that EDF has significantly reduced its nuclear capacity. The same behavior is repeated in *Big 5 – 4* simulations. The key difference is that the two companies that own the strategic nuclear facilities are sufficiently reliant on their profits to discourage them from allowing any dormancy when the price algorithm is applied. With the capacity algorithm, the same nuclear facilities may be willing to withhold an amount of capacity if there are sufficient returns to justify the withdrawal. In *0 years Price Big 6 – 4*, the market is on the cusp of breaking away from the restrictions imposed by the competitive fringe and base load capacity so the effect of nuclear capacity withdrawal is enough to disrupt the merit order pushing market power onto another strategic plant. The analysis of consolidation and decarbonization market settings will further explore the comparative advantages of both *Price* and *Nuclear*. Before that an explanation for the stunted market power in the other two capacity withholding strategies *Wind* and *Wind & Nuclear* is proposed.

Wind capacity withholding

Surprisingly, even in strong decarbonization scenarios where wind power commands a large share of the market, capacity withholding strategies for wind power strictly reduce market power relative to *Price* in all market settings. Graphing *Wind* against *Price* and *Competitive* in Figure XV illustrates this result.

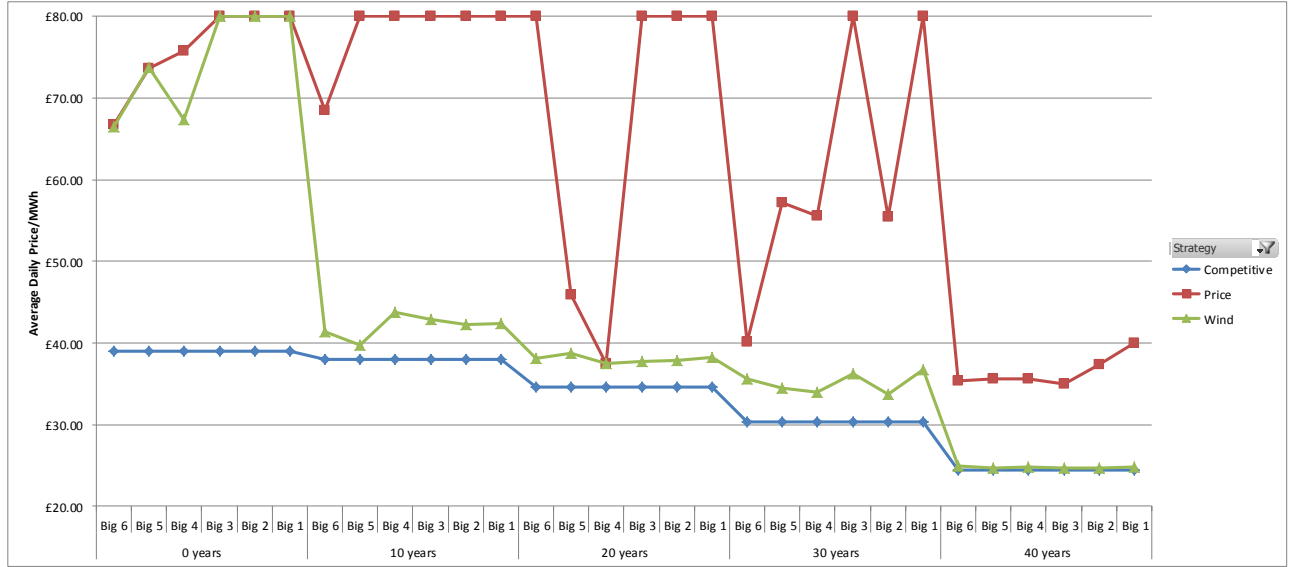


Figure XV

The only market setting in which *Wind* leads to significantly higher prices than *Competitive* is *0 years*. Without decarbonization, wind represents only 2% of the market. About half of this wind power is owned by the competitive fringe whose plants always act competitively. This means wind facilities' profit contribution and market share is minimal. The high levels of market power for *Wind* in *0 years* may well be a reflection of the market power created by *Price*. In other words, the positive influence of allowing technologies to play on price overrides the downwards pressure created by *Wind*.

In order to confirm this theory, information concerning the development of the merit order stack is needed. The model assumes that technologies with negative marginal costs will remain below zero. This assumption means that for the *Price* simulations, strategic behavior on the part of the wind plant is irrelevant. *Price* merit order graphs will intersect the *x* axis at the same point as the corresponding *Competitive* merit order stack. *Wind* simulations allow the same capacity to withdraw some of its production from the market. If significant capacity withdrawal is present it will show up in the merit order graph as a lower intersection with the *x* axis. If the market power in *0 years* is possible despite wind capacity play instead of due to it, these intersections should be similar for both *Price* and *Wind*.

Figure XVI shows evidence that wind withholding has not been formative in the market power of *Wind* in the *0 years* simulations. The triangles on the *x* axes show the demand levels over a 24 hour period, which remains constant over the entire month of December. For the time being, market concentration will be set aside and the following merit order stacks make use of the *Big 6* setting. The difference between the dotted competitive merit order line and the colored merit orders is that the model allows agents to pursue

strategic behavior. The strategic behavior creates a more differentiated market where flat cross sections are less prevalent. Any remaining flat or horizontal sections are the result of the competitive fringe who still offers each plant's marginal cost. Each line forms a merit order stack as of the last daily auction. Note that the axis ranges exclude capacity that has priced itself over the market cap. The similarity between the x axis intersections of *Wind's* red merit order stack is almost identical to competitive levels. Again this indicates that a negligible amount of wind has been withheld from the market. Furthermore the similarity between *Price* and *Wind's* merit order stacks indicates a close correlation between strategic behaviors in both simulations.

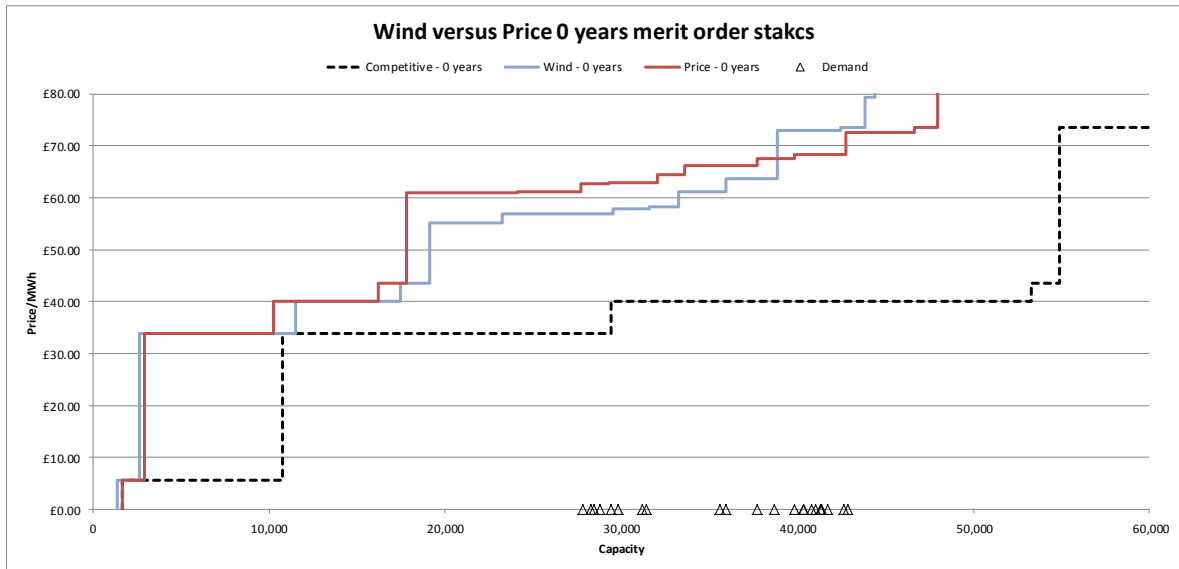


Figure XVI

The justification for wind facilities not withholding significant amounts of capacity comes down to the profitability of wind technology. In the model, offshore wind is projected to have the lowest marginal cost due to government subsidies and resource availability (it does not cost the company anything when the wind blows). The model defines profit as the SMP minus marginal cost. Therefore, per unit of output wind facilities—in particular offshore wind facilities—are the most profitable. This means that withholding wind capacity is subject to a high opportunity cost relative to other technologies. To illustrate, a nuclear facility with a cost of production of 5.6 pounds/MWh will generate 34 pounds of profit given a SMP of 40 whereas an offshore wind facility with a government subsidized marginal cost of -100 will generate 140 pounds for the same quantity. This opportunity cost means wind plants are reluctant withhold capacity and therefore continue to generate base load capacity.

The inflated profit margins do not explain why other strategic technologies in *Wind* simulations are capable of exercising so little market power in decarbonized markets. Figure XV shows that after 0 years,

Wind simulations never again achieve more than a minimal mark up over competitive levels. After all, market power is present in *Price* simulations even though wind facilities have no market power potential when playing on the price algorithm. The answer comes down to the symmetry imposed on the model by coupling different plants to the same profit function.

Corporate profits are calculated as the sum of individual plant profits owned by the firm. Both algorithms link strategic behavior to corporate profits. This symmetry is debilitating to *Wind* simulations because the combined increase in profits provided by other generators owned by the plant are not enough to increase corporate profits if the same iteration coincides with a capacity withdrawal of offshore wind. To decrease the chance that decarbonization has an unequal effect on different companies' market power, each of the Big six companies has at least one offshore wind facility. No additional facilities are given to companies that already use offshore wind but those who do not are allocated one. Instead of smoothing the impact of decarbonization across the big six companies, this assumption essentially evens the playing field by crippling all strategic behavior. Back to the merit order graphs, Figure XVII illustrates this effect.

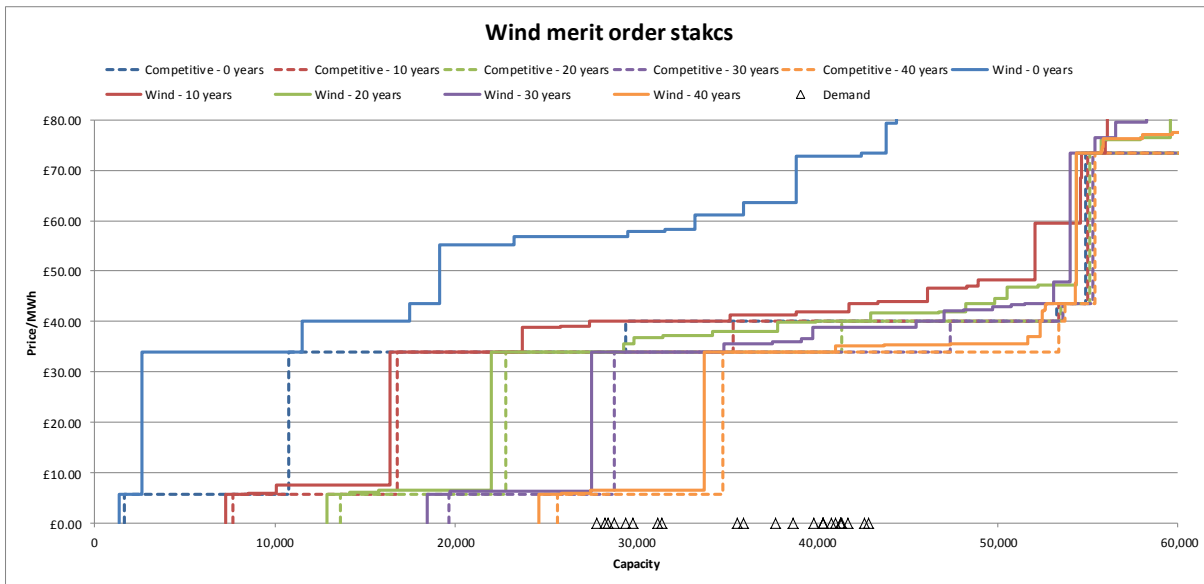


Figure XVII

There are two important observations here. First the solid *Wind* lines never cross the x axis far behind the corresponding competitive scenario. Therefore, not much wind capacity is ever taken out of the market. The second noteworthy trend is that the solid lines at 34 pounds (marginal cost of gas) and above become more and more muted as decarbonization progresses. This is firm evidence of symmetry limiting the market power potential of assets owned by the same company.

Empirically, the rationale of this extreme symmetry in firm behavior is unjustifiable. The model normally compensates for this influence through algorithm variable x which adjusts the scale of strategic decisions. The variation is sufficient to cope with moderate discrepancies in profitability but not that offshore wind. This problem is exacerbated by the large size of offshore wind facilities projected by decarbonization. Offshore wind's relative contribution to corporate profits increase proportionally to the growth in plant size. This is why the latter years of decarbonization are so debilitating for *Wind* simulations. This unforeseen symmetry problem limits the validity and comparability of the model relative to *Wind*. The rest of the thesis centers on the results of *Price* and *Nuclear* but first a brief note on *Wind & Nuclear*.

Wind & nuclear capacity withholding

The results for *Wind & Nuclear* closely mirror those of *Wind* by itself. The only time this observation does not hold is in 0 years. In 0 years wind capacity is almost negligible and as with *Wind*, the results are a shadow of *Nuclear* rather than any indication of *Wind & Nuclear's* validity as a strategy. Using the same graph as before, Figure XVII shows the high correlation between *Wind* and *Wind & Nuclear* is clearly evident.

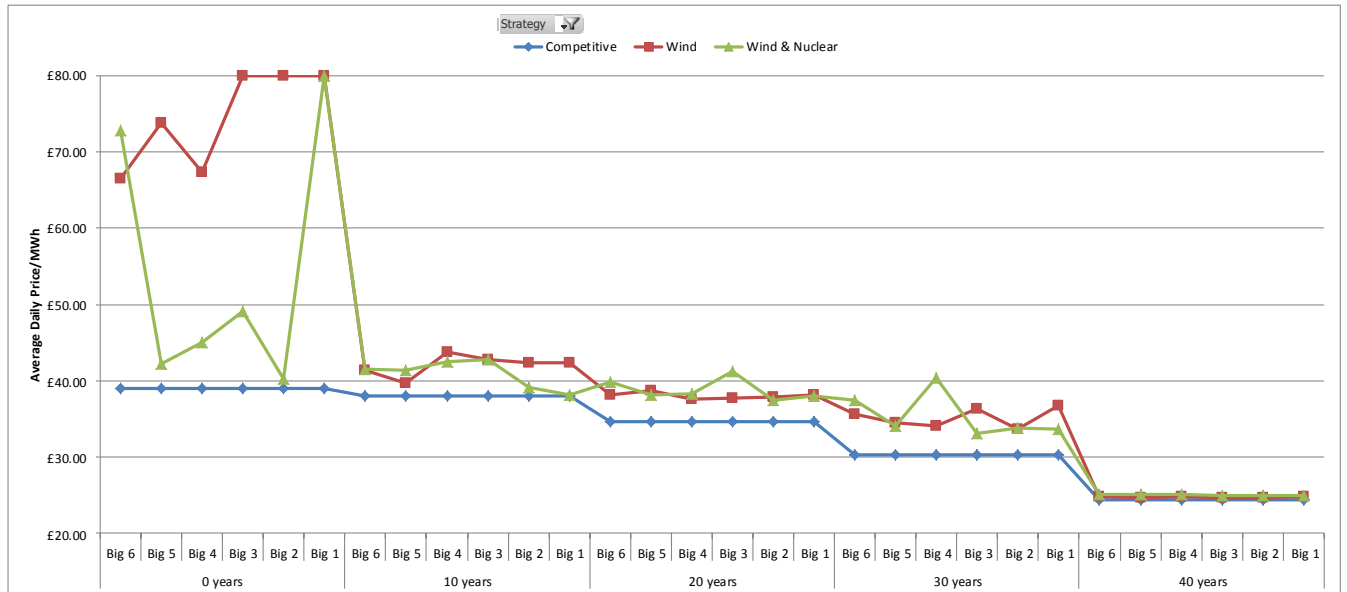


Figure XVIII

These results exhibit the same prolific reduction in market power displayed by *Wind*. Clearly the same symmetry confounds *Wind & Nuclear*. Even though on its own *Nuclear* has significant catalyzing effects on market power, this power is mitigated when combining it with the limitations inherent to wind capacity withholding. Certain applications of the algorithms symmetry are empirically relevant and justifiable. For example plants using the same technology owned by the same company will probably

synchronize their offers. When applied the offshore wind assumptions found in the model its applicability is restricted. Proceeded analysis of capacity withholding therefore uses *Nuclear* as a proxy. In so doing, the comparison of *Price* and *Nuclear* is synonymous with the comparison of strategic behavior based on capacity withholding versus price offering.

Market power versus consolidation

When it comes to consolidation, several data points imply an unexpected relationship between market power and market setting. For the most part, the results are consistent with the conventional wisdom that market power increases with market share. Several simulations, however, show acquisitions to be market power mitigating. The most robust evidence supporting the latter claim is the absence of market power in the *Big 3 - 2 Nuclear* simulations. In these simulations, the transition from four to two/three large companies stymies the strategic agent's disruptive capabilities in almost all decarbonization settings. This phenomenon is present in all but a handful of decarbonization scenarios. Certain *Price* simulations also display an inverted response to consolidation, and while these results are limited to a few decarbonization scenarios, they are nevertheless interesting due to the associations between non-monotonic price developments in decarbonization and concentration levels. The evidence in *Nuclear* points to the importance of individualized behavior when it comes to the effective use of capacity withholding; the *Price* simulations implicate competition as a catalyst for market power. If valid, both results are highly unexpected in terms of conventional liberalization doctrine.

Capacity withholding constraints imposed by acquisitions

By isolating *Nuclear* and repeating the decarbonization scenarios, it is possible to identify the negative impact the *Big 3* and *2* concentrations have on nuclear. Each line represents a separate decarbonization scenario in Figure XIX (*40* and *35 years* omitted). The next section will address the unique distortions caused by these two extreme decarbonization settings that eclipse the impact of consolidation and *Nuclear*.

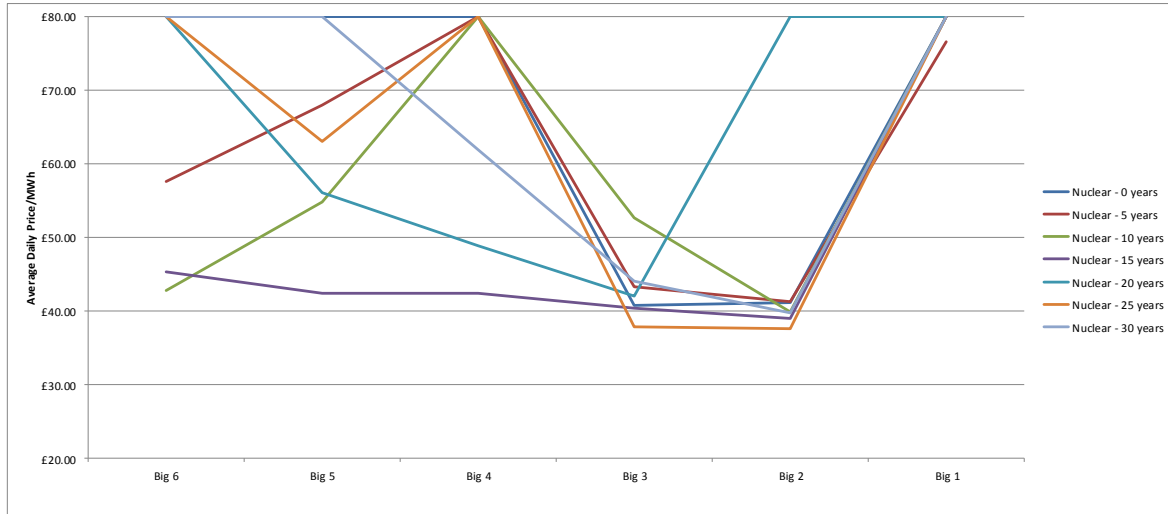


Figure XIX

Nearly every *Nuclear* simulation becomes less potent in the *Big 3* and *Big 2* market concentrations. Concentration as a whole, however, does not strictly decrease market power. In all settings prices rise again in *Big 1*. Higher market concentration in *5 years* and *10 years* lead to increasing prices before dropping at *Big 3*. Since the same limitations are not evident in *Price* data, the importance of *Big 3* and *Big 2* is isolated to the effect consolidation has on the portfolio of companies that have nuclear capacity. The effect of this transaction then dissipates in the last transaction that unifies the strategic market. Breaking down the structure of each acquisition may give at least a partial answer to this result. Luckily there are only three nuclear facilities, one of which is operated by the competitive fringe. The two remaining plants are owned by CEN and EDF. CEN's facility generates a real available capacity of approximately 1,600 megawatts. EDF's generator is significantly larger and has a real available capacity of approximately 6,300. The bar graph below breaks down real available capacity by market concentration for the *Big 4 - 2* concentrations. Figure XX compares each company's the portfolio composition by acquisition as of *0 years*.

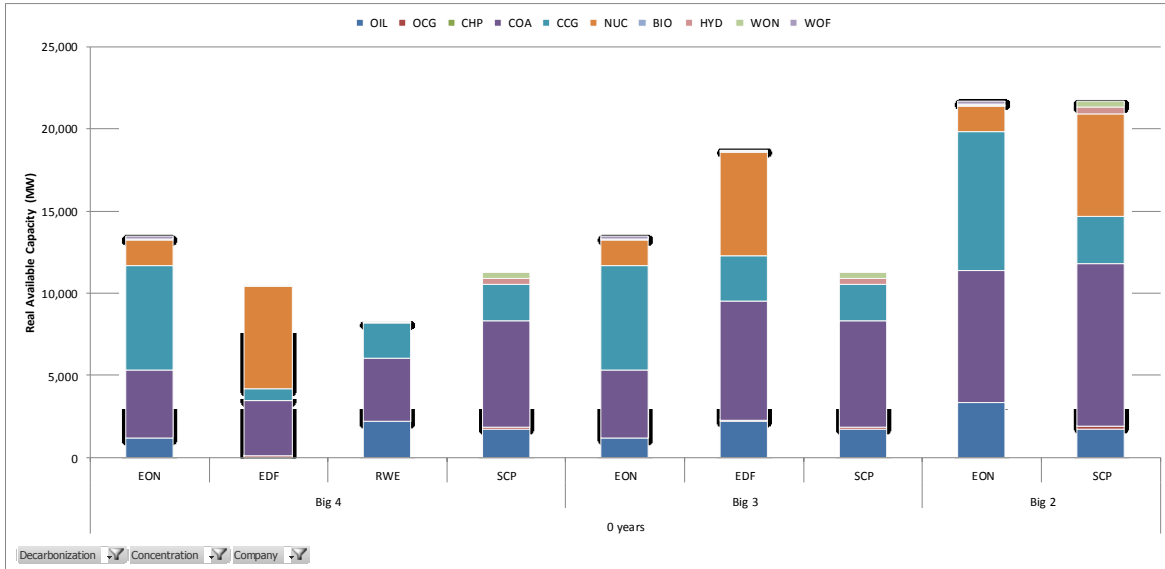


Figure XX

Instead of a change of ownership of a nuclear facility; in *Big 3* EDF purchases RWE leading to a more diversified company portfolio for EDF who still owns the large nuclear facility. In *Big 6 - 4* a majority if EDF's capacity is generated by the one nuclear facility. The acquisition in *Big 4* diversifies EDF's portfolio to by adding oil, coal and gas capacity. Instead of dramatic shift in EDF's behavior, this result is due primarily to RWE's role in promoting market power.

Looking at RWE's portfolio as of *0 years*, we see that excluding small wind and hydro facilities, the company has three plants; one uses gas, the second uses coal, and the third uses oil. Overall RWE starts with the lowest profits of all of the companies. Of the three plants, only the gas facility is included in dispatch in the first iteration no matter the market condition. Gas technology is unique in that in all market conditions (excluding *40 years*); the market always needs at least some strategic gas capacity before strategic behavior alters prices. This gives gas facilities leverage to increase prices at least to the next most expensive technology. The model's algorithms use profit information from all plants to determine whether or not to continue acting strategically. Only having one plant used in production simplifies the decision making process for a firm. In this way, companies reliant on one plant for most of their profits will be more efficient in exploiting market power. RWE is often one of the first gas plant owners to exploit its position. Before decarbonization reduces its capacity, RWE's coal plant is capable of producing almost double the capacity of the gas plant. Because of its relative size, the coal plant can quickly make up for the difference in profitability between the two technologies. By having a gas and coal plant RWE is capable of playing the market from two angles if and when its coal plant is needed. Even though all companies have at least one

gas and one coal plant, RWE's two plants seem to be of ideal size compared to one another when it comes to market power potential.

By combining these characteristics, a company can be uniquely suited to aggressively increase prices. EDF limits behavior of the same plants that RWE used to manipulate the market. On its own, EDF has a large nuclear plant, a small gas plant, and an average sized coal plant. In the first iteration both the nuclear and the gas plant are producing. Figure XXI breaks down how the nuclear, gas, and coal plants owned by either EDF or RWE respond. The graph contains three sets of data presented across the first 100 iterations. Only 100 iterations are included because already by then prices are diverging above the price cap. The colored areas in Figure XXI are plotted on the primary axis to the left, measuring the profits of each plant. Each area set has a corresponding line graphed along the secondary axis. Here each line relates to the plants price offer. The black line gives the average daily price which is used as a measurement of market power. Note that a plant can generate profits when their offer is above the average daily price by dispatching only during peak periods. This is true of RWE's coal plant. Lastly, the thick orange line tells us how much capacity EDF's nuclear facility has withdrawn. The line is plotted against the secondary axis and measured as a percentage of real available capacity.

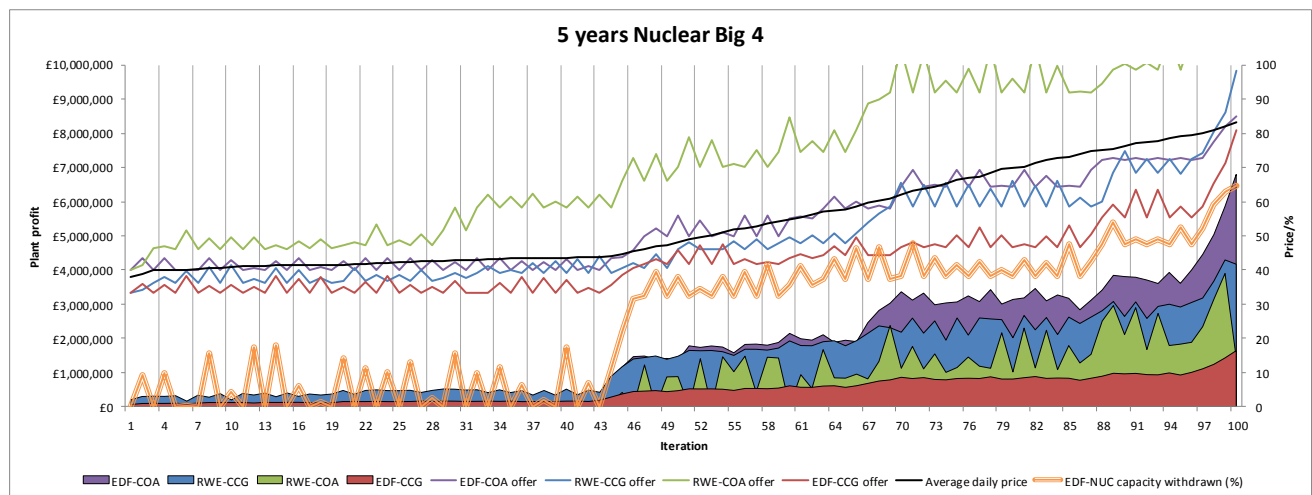


Figure XXI

While market power is not evident until around the 44th iteration, RWE's aggressiveness is apparent in all iterations, offering its capacity at a higher price than EDF's corresponding facilities in all but a few iterations. In fact, RWE's gas plant is more in line with EDF's coal plant when it comes to price. The correlation is not a coincidence; gas capacity trying to "push itself" past coal is a frequent feature of these simulations. The withdrawal of nuclear capacity around the 44th iteration is successful for two reasons. The most noticeable influence is that RWE's coal plant is included in dispatch, enabling it to exercise price

discipline at peak hours. The emergence of the green area after the 43rd iteration is clear evidence of this result. In *Big 4*, EDF is a separate company from RWE and therefore the second reason capacity withholding is effective is that it also coincides with increasing profits for EDF. Figure XXI tells us that EDF's gas facility (EDF-CCG) is almost always included in dispatch because its price is consistently lower than the average daily price. This observation is reinforced by the fact that when prices begin to increase after the 44th iteration, the red area grows at roughly the same rate as average daily prices. If the nuclear capacity withholding had pushed the plant into dispatch for more hours of the day, the plant would experience a stronger boost to profits. Compared to its gas plant, EDF's coal plant experiences a substantial boost when the capacity is withdrawn. Before nuclear capacity is taken out of the market, this coal plant is only needed when RWE's gas facility is higher than its own. RWE is reluctant to cross this threshold because without profit contribution from its coal plant, RWE relies heavily on its gas capacity for profits. The competition between these two plants—combined with the competitive fringe's coal capacity offered marginal cost of coal—limits prices to around 40 pounds. When nuclear capacity is taken out of the market, EDF pushes its coal plant into production even if RWE's plant is stacked lower in the merit order. Both plants are also freed from the influence of competitive fringe. On EDF's behalf withdrawing capacity is profitable in the short run when it bumps its coal plant into dispatch. In the long run, RWE will continue to exert aggressive price discipline reinforcing further withdrawal.

The question becomes how and why, under identical market conditions, does putting the same facilities in EDF's name handicap the company's ability to distort the market? In Figure XXII, the same information as Figure XXI is presented for *Big 3* (which means EDF now owns RWE's assets).

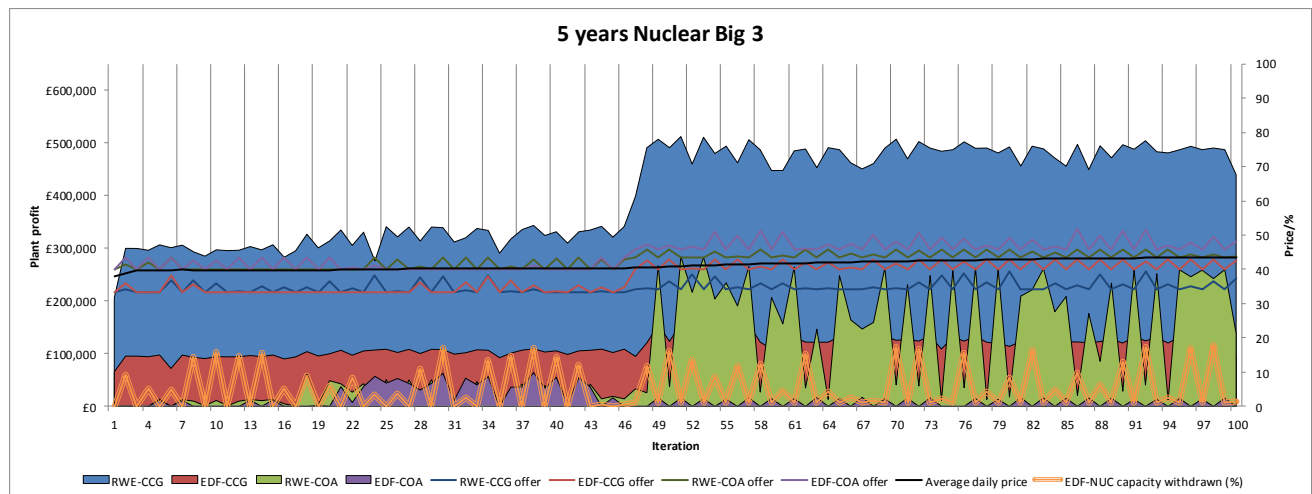


Figure XXII

When separate from EDF in the first 30 iterations, RWE-CCG moves its offer up to that of EDF-COA and RWE-COA moves its capacity to a price well beyond the average daily levels. Now, however, both plants are in line with EDF's plants which offer capacity at near competitive levels. Interestingly, both RWE's plants receive a large boost to profits around the 46th iteration; roughly the same time when prices began to increase in *Big 4*. This detail indicates that a factor exogenous to these two companies is responsible for triggering market power. Neither SCP nor EON is included in the figures so the spark almost certainly came from some strategic behavior on their behalf. Nevertheless, it is curious that prices do not begin to increase after this shock; this outcome raises questions concerning the influence of consolidation on the market. The colors are synonymous for Figure XXI and Figure XXII. In the *Big 4* setting the purple EDF-COA section becomes the most profitable plant of the four shown in either figure. In contrast, for *Big 3* the same section all but disappears after the 46th iteration. This result comes from the limitations imposed on the market by not having RWE clear out its coal and gas plant at lower price levels. RWE's behavior is so critical because the differentiation means that the gap in the merit order created by withdrawal has an immediate effect on prices. This reduces the decrease profitability felt by the company withholding capacity in the short term. In the long term these differentiated price offers contribute to market power by providing the strategic agents more leeway before running into another price level.

The interaction between nuclear capacity withholding and market power is analogous to an American Football team with a running back and a blocker. The running back represents the strategic price players at or around the margin where demand intersects the merit order. The nuclear plant is personified in the blocker. On its own, the blocker is not capable of running with the football and will never gain many yards for the team on its own. The running back on the other hand, is good at running with the football but will sometimes need a blocker if the opponents are in the way. The blocker is only effective if the running back is behind him or her. Without a capable running back the blocker has no use. This is precisely the problem with the *Big 3 - 2* nuclear capacity withholding strategies. EDF's nuclear capacity withholding is effective when paired with the ability of RWE to aggressively increase prices. In other words, RWE is a good running back. When RWE's plants are purchased by EDF, they lose effectiveness the offence breaks down. Why the running back becomes ineffective comes down to the effect consolidation has on the running back themselves rather than the blocker. Expanding on the same metaphor; by putting RWE's plants in EDF's name the acquisition ties together the feet of the combined entity's running backs and the blocker. The behavior of each player impacts the system as a whole and the players start to stumble over each other.

Simulations where decarbonization has reduced the capacity of RWE's coal plant limit the company's exploitive behavior. Prices still diverge for less concentrated *Nuclear* simulations because of the

non-monotonic relationship between decarbonization and *Nuclear*. This association is already discussed at length above, but essentially after a lull around *15 years*, market power rebounds in *Nuclear Big 6 - 4* as the increasing effectiveness of nuclear capacity withholding counteracts the waning aggressiveness of RWE. *Big 3* and *Big 2* are unable to make use of the positive effect non-monotonic decarbonization has on *Nuclear*. Only once between *0 - 30 years* do prices exceed the cap for either *Big 2* or *Big 3*. This isolated data point came about due to chance synchronization allowing the two remaining firms to act as one entity.

Both *Nuclear Big 3 - 2* simulations reap the unique conditions that the *35 years* decarbonization scenario creates for *Nuclear*. This setting is already analyzed as it applies to *Nuclear Big 6 - 4*, and the same rationale can be applied here. Basically, by *35 years* the merit order has been shifted far enough to the right that nuclear plants are actually included in dispatch for several hours of the day. This gives both facilities an immediate ability to withhold capacity which they do. The early withdrawal of nuclear capacity combined with the diminished coal capacity of the competitive fringe provides excellent conditions for *Nuclear*. Even then, *Big 3* is unable to increase prices above 62 within the span of 200 iterations. The impetus provided by latter decarbonization settings is stymied by the *Big 3* merger. To a regulator looking at market concentration, these results imply that certain acquisitions may be able to reduce market power. Proceeding sections contain a more detailed discussion of the policy implications.

In short, what has happened in the *Big 3 - 2 Nuclear* simulations is that consolidating assets under the same company leads to a less differentiated price structure in the market. EDF does not imitate the early strategic behavior development of RWE's facilities because assets owned by same company pursue far too similar behavior. The model creates additional differentiation (in less consolidated markets) implicitly through aligning the algorithms with company profits. This is especially important when a company owns two facilities using the same technology. In the model plants using the same technology will always have the same starting point. This means the only variation in price between the two plants comes from the randomly generated scale variable x in both algorithms. X will never grossly differentiate the offers of two plants under the same technology and owner because any variation still trends in the same direction. Empirically speaking this result is quite logical, but production costs are not as simple as the model assumes. Two separate companies owning a natural gas generator will have different cost structures. Perhaps one company could be more efficient in managing overhead costs or could have signed favorable raw materials contracts. These circumstances would lead to differentiated price levels. On the other hand, if one company owned two natural gas generators it would be reasonable to assume that the two facilities share similar production costs.

A caveat is needed to explain how *Big 1* is able to break free of the constraints that crippled *Nuclear's* market power in *Big 3 - 2*. Strategic behavior in *Big 1* simulations adhere to a strict regimen.

Price discrimination is severely limited when all strategic facilities are aligned under the same entity. This feature of consolidated markets is debilitating for both *Big 3* and *Big 2* scenarios, but *Big 1* has the distinct advantage of total synchronization. This term refers to the momentum generated by all agents increasing strategic behavior in unison. If any market power is present, the resulting increase in company profits will cause all of the strategic facilities to increase their offers. Synchronization moves such a substantial amount of the merit order that any prolonged increase in the company's profit totally wipes out capacity at lower price levels. The only threat faced by the *Big 1* is that there is not sufficient market power initially to clear out capacity and offers converge. Price differentiation can be similarly limited when all plants are under the same management. By associating all strategic capacity with the same entities profit, offers tend to cluster if prices remain constant. The result is that *Big 1 Nuclear* simulations can have a hard time clearing the price hurdles of the competitive fringe. This is not a problem in *Price* simulations. Since nuclear capacity is included in dispatch in all market conditions, *Price* simulations grant nuclear capacity. For *0 - 35 years Nuclear Big 1* simulation that failed to achieve a price above 80 is in *5 years*. This result highlights the potential problem of extreme offer conformity. Prices stagnate at around 40 pounds for more than 150 iterations because not enough momentum is generated early on in the simulation. In the final 20 iterations, the variance in the algorithm has allowed all of the company's coal and gas to clear the competitive fringe. The company thereby regains momentum and prices begin to diverge exponentially, but given the limited number of iterations remaining the results show an average daily price of 76.637 as of the last iteration.

Returning to the football metaphor, what has happened is that enough running backs have been united in *Big 1* that provided they gain enough momentum, their combined movement will carry them forward. The block provided by nuclear capacity withholding is effective if and only if the running backs have gained enough momentum to carry them. Looking to the results of *Nuclear Big 3 - 2*, synchronization is prohibited due a lack of sufficient consolidation of capacity. The *20 years Nuclear Big 2* simulation generates results above the price cap due to chance synchronization between the two remaining firms. The standard result, however, is that not enough capacity is taken out of the market at low prices to warrant nuclear withdrawal. The synchronization is so difficult because full cooperation is needed by all of the two or three firms before the same effect is triggered. The chance that one plant's profits end up excluding the company as a whole from participating are far greater with two or three large firms.

Competitions role in realizing a differentiated merit order

Changing the algorithm selection from price to capacity for the two strategic nuclear facilities negates the constraints imposed by *Nuclear*. Prices are above the cap for all *Big 3 - 2 Price* simulations until *30 years*. At this point the aforementioned non-monotonic decarbonization influence erodes market power for *Price*. Yet, *Big 3 - 2* prices are roughly equal to or greater than those in less concentrated markets.

Nonetheless, consolidation data from *Price* has its own idiosyncrasies that fly against expectations. The evidence is far from consistent and only visible in a handful of *Big 6 - 4* simulations exhibiting an inverted relationship between consolidation and market power. A more thorough investigation is imperative in order to decide whether or not the results are relevant to policy makers or merely a chance exception. First let us refer back to *Big 6 - 4 Price* data repeated in Figure XXIII which provides a clear view of the trend in question.

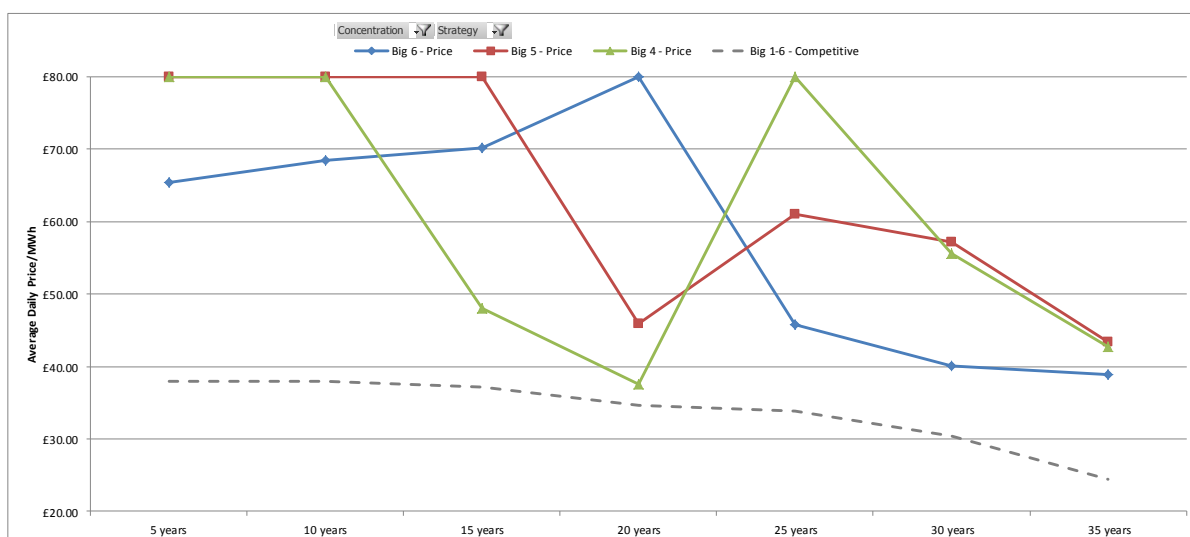


Figure XXIII

Big 6 is strictly lower than all other *Price* market settings before *15 years*. Interestingly, *Big 6* increases potency and peaks at *20 years*. Contrastingly, *Big 5 - 4* bottom out in *20 years*. In *25 years* both *Big 5 - 4* experience a short-lived revival before again decreasing. *Big 6* on the other hand decreases sharply after *20 years*. The difference between *Big 6* and *Big 5* is the acquisition of Centrica by E.ON. There are two questions that need to be addressed separately, first, how is *Big 6* able to capitalize on moderate decarbonization in *20 years*, and second, what prevents *Big 5 - 4* from benefiting from the same influence. Looking at Figure XXIV we see that the structure of the market is considerably different in *20 years* than it is in *0 years* given amount of decarbonization.

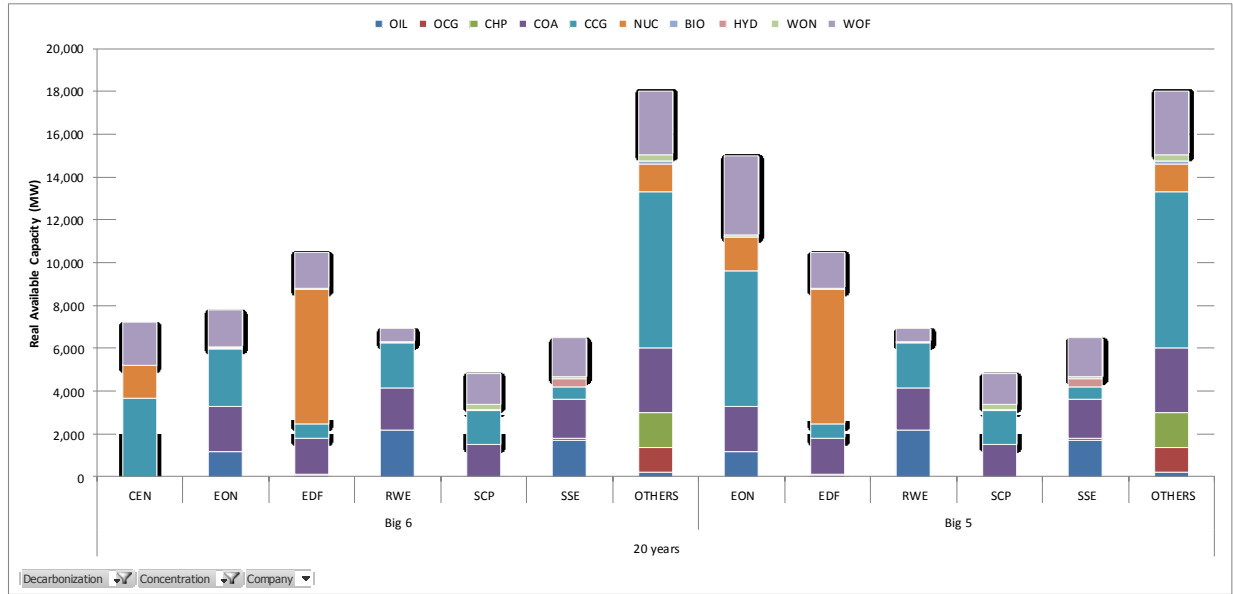


Figure XXIV

The capacity of coal, shown in purple, has diminished and been replaced by offshore wind farms which are visible as the light purple color on the top of each companies bar graph. Figure XXIII Figure XXIII shows that market power is at a low for *Price - Big 5* even though it is at a high for *Price - Big 6*. By purchasing CEN, EON has stymied market power potential. The crucial element here is the behavior of the CEN's and EON's gas facilities before and after consolidation. Surprisingly, the behavior of CEN's nuclear facility is irrelevant. In *Big 6* the plant does not exert any market power during the critical iterations when prices begin to diverge. Figure XXV examines the behavior of both gas and nuclear plants owned by either CEN or EON. Note that the graph only spans 100 iterations which is enough time for prices to begin to diverge.

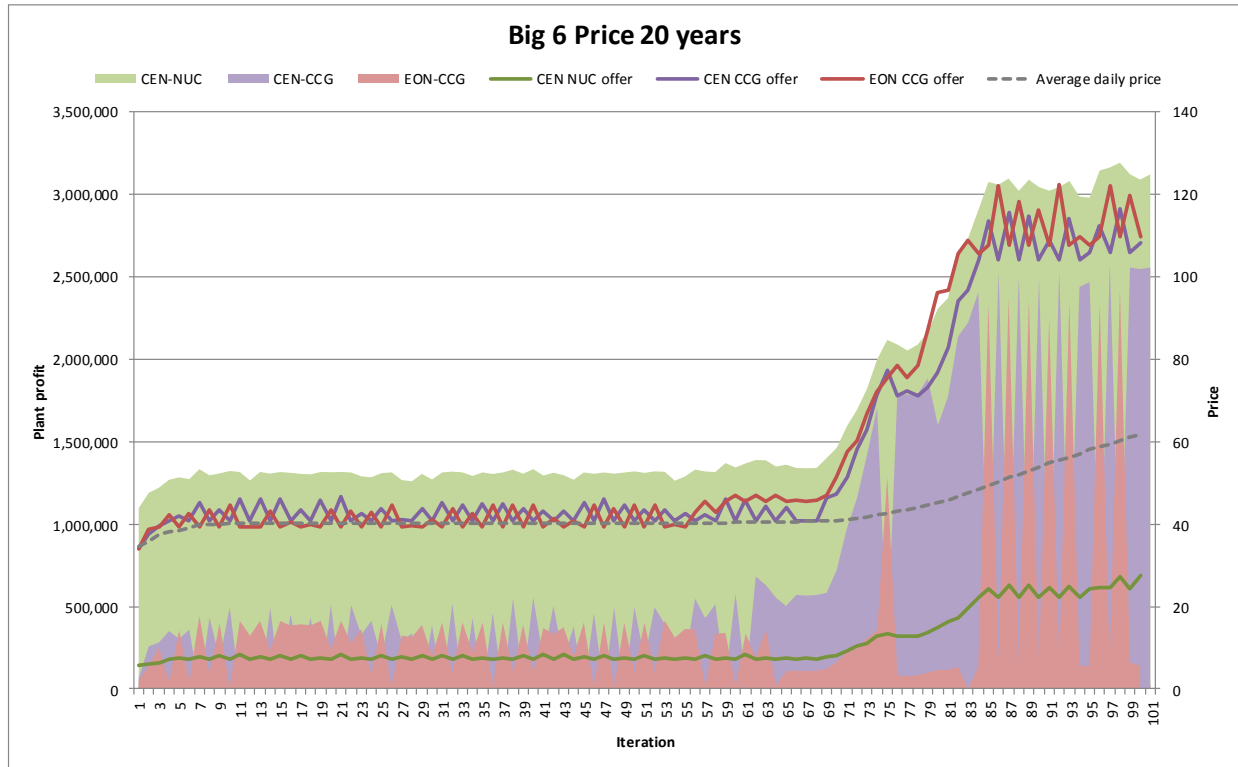


Figure XXV

The colored areas in Figure XXV are plotted against the primary axis. Each represents the total profit generated by an individual plant. The lines are plotted against the secondary axis. The dotted line shows the development in our market power barometer, average daily prices. The solid lines indicate the offer price correspond colored plant. First, note that the green line is never close to the dotted line over all 100 iterations. CEN's nuclear facility never influences prices. The green area showing the plant's profit grows due to the upward pressure gas technology puts on prices. Around the 70th iteration prices begin to diverge. This is the first prolonged period where one of the two gas facilities owned by either EON or CEN is strictly higher than the other. In this case, EON's gas plant is above CEN's. This gives CEN the power to increase prices at least up to the offer of EON's plant. Prices accelerate because as CEN increases its offer, EON's profit as a company is also increasing. This leads to higher offers for EON's gas facility which stays above CEN's gas plant allowing it to continue to increase prices. Over this period profits more than double for CEN gas plant. Average daily prices are not increasing at the same rate as the offers because during low demand hours, there is still sufficient capacity without the two gas plants. Peak hours however are at the mercy of the strategic gas. Eventually the offer of EON's plant drops to below that of CEN's plant first one time around the 75th iteration, then over and over again from the 85th iteration onwards. When this occurs, profits for CEN drop while EDF gets a huge boost since they are now included in dispatch rather than

CEN. Eventually, EON will realize that it is better for them to allow CEN to take over dispatch and prices continue to diverge.

What has happened is that the competition between CEN and EON's gas plants forces prices upwards. CEN does not care if EON is less profitable. If CEN can increase prices and simultaneously keep them lower than that of EON's gas plant, both end up benefitting even though in the short term EON's profits drop. What is not pictured in Figure XXV is EON's other capacity that is reaping the benefits of increased prices. Remarkably, what has happened is that competition between CEN and EON is increasing market power. If this is true, introducing competition can decrease the efficiency of an electricity market. To find out if the competitive behavior of CEN and EON's gas plants is in fact to blame, Figure XXVI plots the same plants behavior in identical market conditions. The only difference is that EON has purchased CEN.

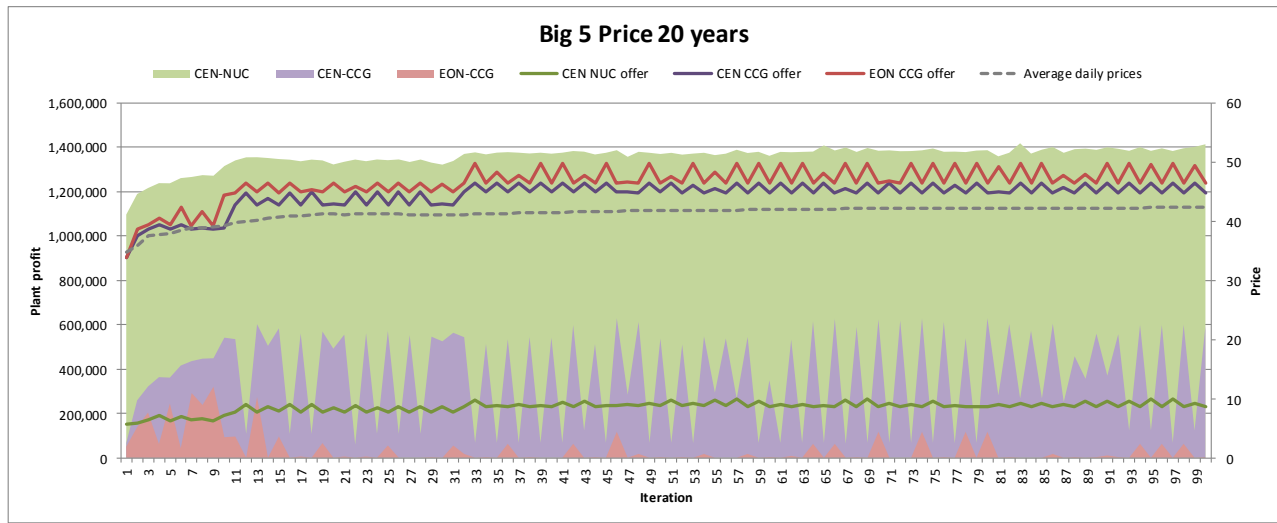


Figure XXVI

The nuclear facility is irrelevant as it was in *Big 6* when it comes to price setting. The two gas plants, however, are now unable to distort the market. Unlike last time EON's gas plant is strictly lower than CEN's for the all iterations. This plant then has the ability to increase peak hour prices but never does so. Its decision not to increase its price is a direct result of its combination with EON's gas plant. Now that the plants are under the same management, there is no chance of asymmetric behavior between the two plants. In the *Big 6* simulation EON essentially made a mistake that allowed CEN to overtake its market share. This shortsighted mistake turns out to yield long term profitability for both companies because of the market power bestowed upon CEN.

It stands to reason that EON will offer a similar price for two facilities with the same production cost (remember that the model assumes no information dissipation). The company as a whole is oblivious to the fact that it's one gas facility has significant influence over the SMP. In the short term, the marginal impact the one gas plant has on prices does not warrant increasing the offer. Due to the strict correlation between the two offers, one plant will not deviate too far from the other and increasing prices congruently disrupts the positive impact competition may have on market power. There might be a slight difference between the two, but the company does not want to cannibalize its own facility. If profits are lower for the company they will lower the offer price of all their assets.

This effects the market power of other strategic agents because EON is leaving cheap capacity at near competitive levels. If, for example, a dispatching gas plant decides to increase it's the price of its capacity, EON's gas plant that is currently not being used to full capacity will step in and push the higher offer out of dispatch. The model neglects the possibility of an owner taking a long term decision to temporarily decrease profits so that they can exploit prices and eventually generate higher profits. EON could have acquired CEN and then shut down its facilities in order to promote the market power of its other assets. This action would be clearly visible to regulators though and it is unrealistic to think they would ever get away with it. The model then uses reasonable assumptions to imply competition can reduce market efficiency.

Non-monotonic evolution of the price formation with increasing decarbonization

The results from both *Price* and *Nuclear* contradict expectations when it comes to the effect of decarbonization. The code interprets decarbonization as a linear substitution of offshore wind capacity for coal based electricity production. Technology based on wind is assumed to have a much lower operating cost and the model never allows wind to increase offer price above zero. The process therefore adds a cheaper technology that is unable to act strategically in both *Price* and *Nuclear*. Furthermore, wind is substituted for coal, a technology predicted to be instrumental in the formation and propagation of market power. Intuitively, market prices will decrease monotonically with decarbonization. Interestingly, not only is this prediction wrong, but decarbonization appears to effect market power differently depending on which strategic behavior is used. To uncover the mechanisms at play here proceeding analysis will continue the comparison of *Price* and *Nuclear* within the context of decarbonization. The difference in how each strategy is able to cope with substituting wind for coal proves to be instrumental in analyzing the non-monotonic results. The discussion also develops the topic of capacity withholding's relative strength.

Figure XXVII plots out the developments for *Nuclear* under decarbonization. The 40 years decarbonization setting is excluded from the x axis due to the conformity displayed by all simulations when offshore wind has completely replaced coal.

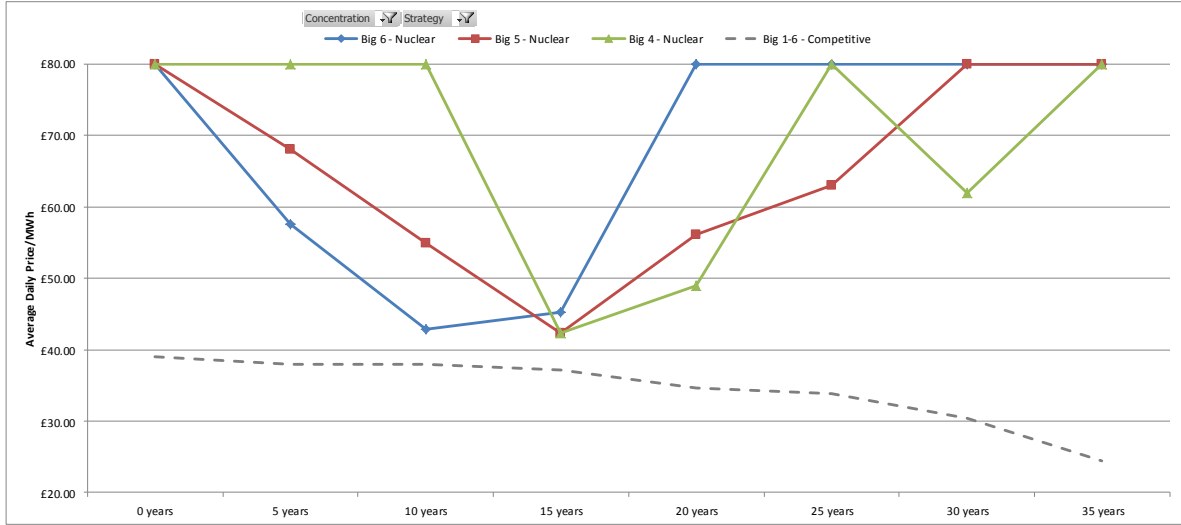


Figure XXVII

The non-monotonic response to decarbonization follows a consistent pattern in *Nuclear*. All three consolidation settings decrease monotonically in the early stages of decarbonization, dropping to near competitive levels. The non-monotonic response to decarbonization comes after 15 years. Interestingly, the price formation in the latter stages of decarbonization is perfectly inverted with the exception of one outlier. In 15 - 35 years *Nuclear* simulations increases monotonically for *Big 6 - 5* consolidation settings. In particular, *Nuclear - Big 5* shows an almost perfectly inverted relationship in the second half of decarbonization scenarios compared to the first. *Big 5* is unique in that each company has relatively similar capacity levels when it comes to coal. The similarity means each company is subject to the same or similar influences as carbon technologies are taken out of the market. The non-monotonic formation in *Price* simulations is less consistent along the different consolidation settings. *Big 5 - 4* simulations are partially distorted due to the effects of competition outlined in the last subsection. Figure XXVIII makes use of the *Big 6 Price* data.

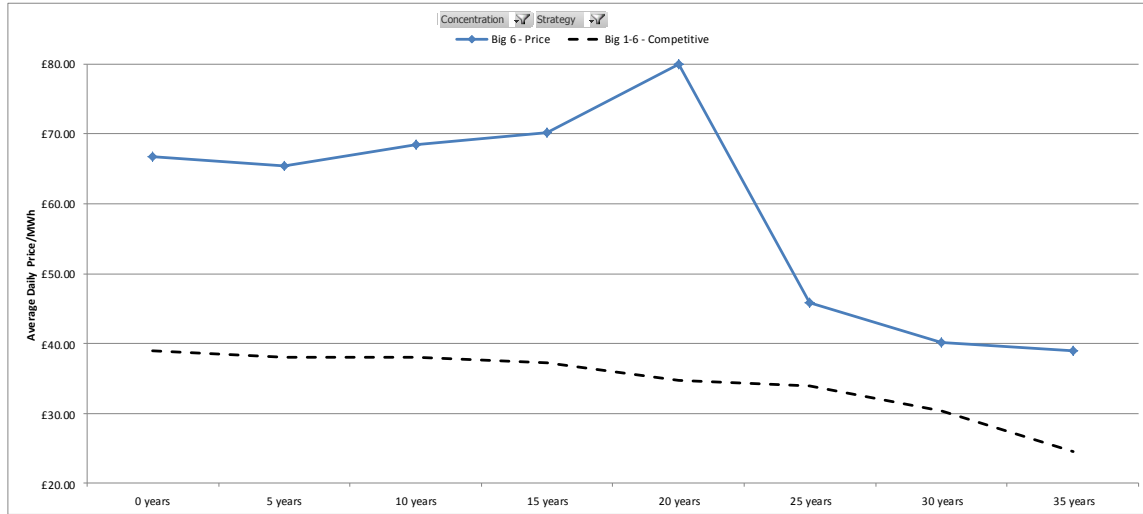


Figure XXVIII

Big 6 Price simulations respond to decarbonization favorably in early settings followed by a monotonic decrease in *20 - 35 years*. This response is opposite that of the *Nuclear* simulations in Figure XXVII. Comparing the two strategies, the non-monotonic response for *Price* and *Nuclear* simulations are opposites. The results of all *Big 6 - 4 Price* and *Nuclear* simulations corroborates this story. Figure XXIX contains results for all decarbonization scenarios for *Price*, *Nuclear* and *Competitive* strategies in the *Big 6 - 4* consolidations. *Price* simulations are strictly higher than those of *Nuclear* in the early years of decarbonization. The same simulations are strictly higher for *Nuclear* simulations after *15 years* until *40 years*.

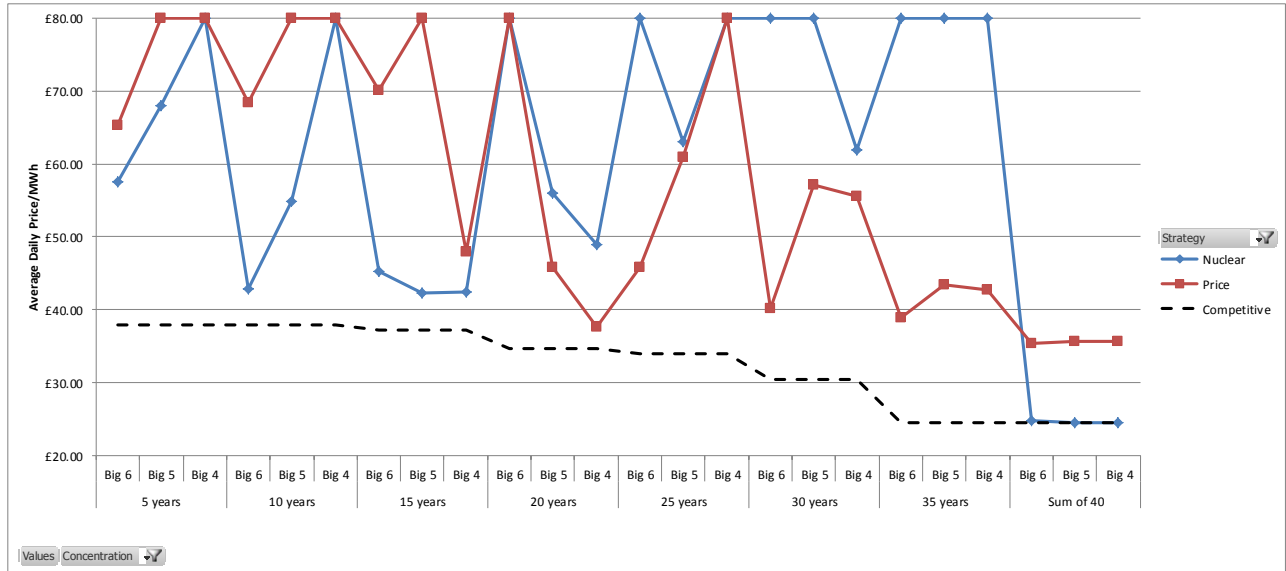


Figure XXIX

The results can therefore be divided into three sections: initial phase of decarbonization characterized by dominance of *Price*, the second section is characterized by *Nuclear's* ability to capitalize on decarbonization, the last section relates to the completely decarbonized market in 40 years where *Price* has a distinct advantage although both strategies converge towards competitive levels. Before delving into each section, it is important to outline the effect the decarbonization assumptions have on the merit order stack. Figure XXX presents the development of the competitive merit order stacks on a 10 year basis. Each merit order stack displayed here represents the starting line so to speak. Competitive merit order stacks show us what the market would look like if there is no strategic behavior.

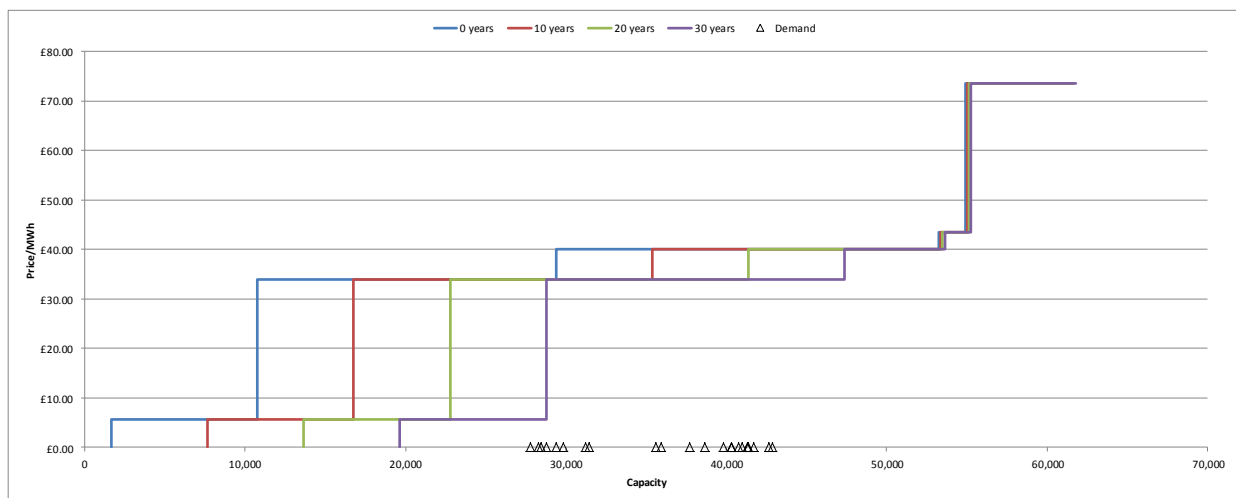


Figure XXX

Diminishing coal capacity is evident in the smaller cross sections at a price of forty. In 40 years all coal capacity has been replaced by offshore wind. The increase in offshore wind pushes the intersection of each line to the right given wind's negative marginal cost.

Phase one: decarbonization empowering price behavior

As decarbonization assumptions begin to replace coal with wind, *Price* overtakes *Nuclear* as the dominant strategy. Over this period, the monotonically decreasing price formation in *Nuclear* is consistent with expectations. Nevertheless the results are worth exploring. In 15 years *Nuclear* simulations bottom out at near competitive levels. Looking at the merit order stacks in Figure XXXI it is possible to see the nuclear capacity providing close to competitive levels.

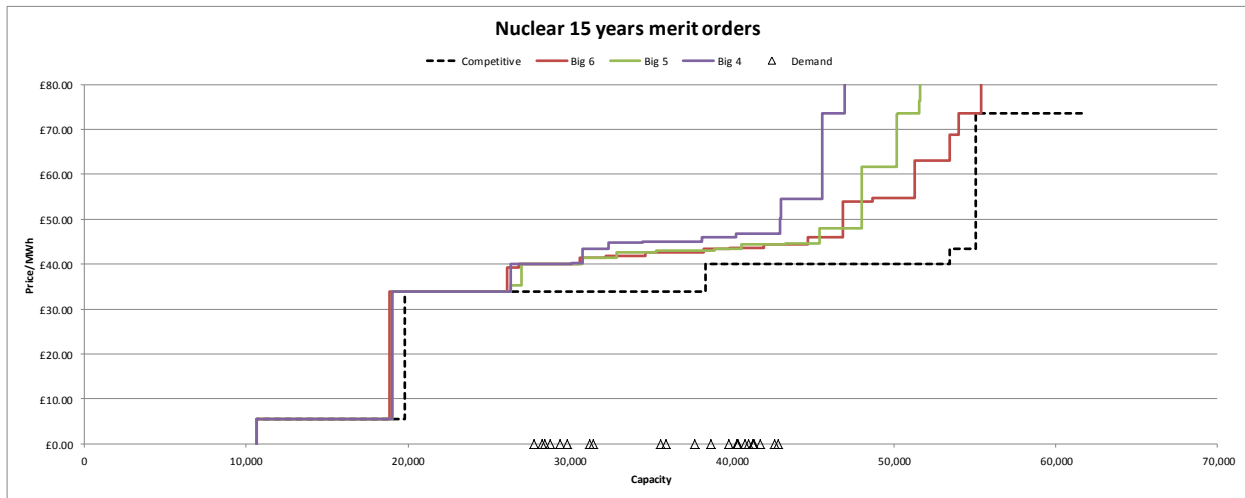


Figure XXXI

At a price of 5.6, each strategic scenario almost completely overlaps the competitive merit order stack. The competitive fringe's gas, coal, and combined heat and power capacity is represented by the flat cross sections above the nuclear capacity. In 15 years the strategic plants with a negative marginal cost account can now produce 1,919 megawatts of capacity. The competitive fringe has the capability of producing 25,972 megawatts. With the strategic nuclear facilities, which we know from Figure XXXI are producing at almost full capacity, the non-disruptive capacity reaches 33,831 megawatts. The same calculations in 0 years come to 27,040. The comparative advantage *Nuclear* hold over *Price* in 0 years lies the fact that only a small quantity of nuclear capacity withdrawal is needed to empower strategic coal and gas facilities. By adding base load, nuclear operators need to withhold a larger amount of capacity to promote the same effect. As we see in Figure XXXI, they are unwilling to do so.

Contrary to *Nuclear*, *Price* simulations generate more market power in early decarbonization scenarios. *Price* only differs from *Nuclear* in the algorithm selection of these two plants. How early decarbonization empowers *Price* simulation comes down to EDF's nuclear plant. By shifting the merit order to the right, decarbonization pushes the nuclear facility closer and closer to the SMP. When playing on price, EDF's nuclear facility is able to increase its offer and set the SMP. Decarbonization promotes this process by moving nuclear capacity closer to the intersection of demand. Given EDF's nuclear facility's large size, as long as strategic coal and gas plants sufficiently clear out their offers, EDF's nuclear plant is more or less free to determine market prices. What we see in Figure XXXII is that EDF-NUC consistently increases prices without significantly influencing the EDF's utilization rate as a whole.

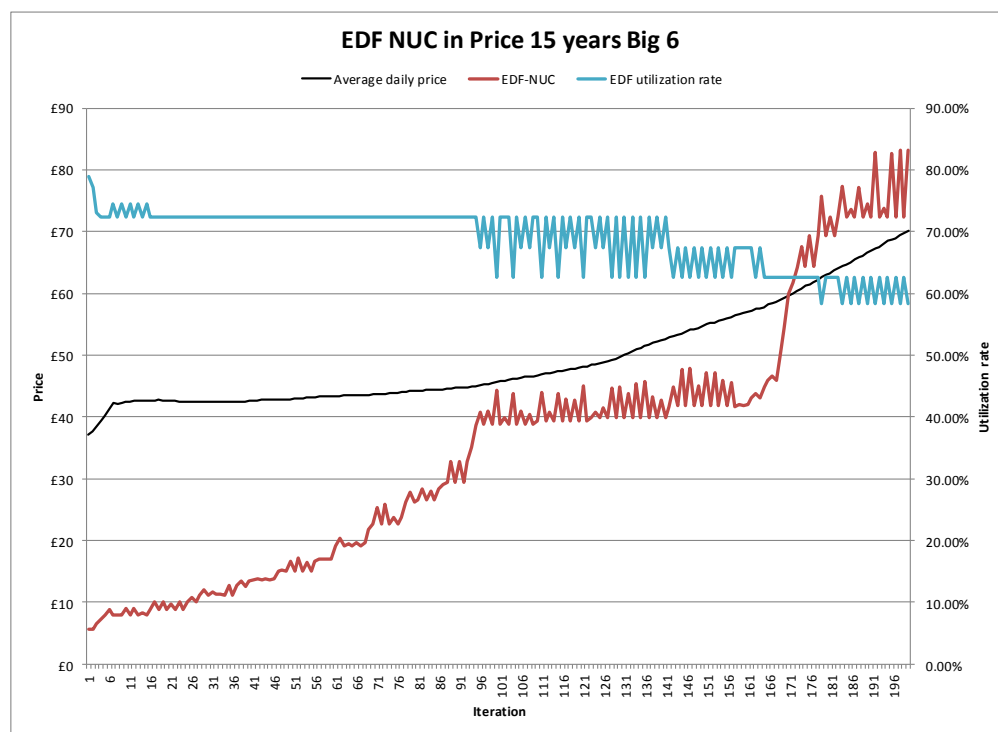


Figure XXXII

Even when the plant increases its offer above the average daily price, it is still included in enough hourly dispatch periods that the company's utilization rate only drops to 10%. Also the average daily prices are clearly impacted by EDF-NUC. Prices do not begin to significantly increase until the facility has increased its offer. Prices start a slow increase at around the 50th iteration once EDF-NUC begins to set higher prices during low demand hours. When EDF-NUC offer reaches a price of 40 pounds, prices begin to increase more rapidly quicker. Figure XXVIII shows that *Price Big 6* generates a gradual increase in market power with decarbonization because more decarbonization decreases the amount of iterations before EDF-NUC is able to start influencing the SMP. Why the relationship is not monotonic comes down

to the natural inherent variation in the offers. The process by which *Price* simulations exploit market power is more or less unchanged between 5 - 15 years. First strategic coal and gas plants price themselves above the SMP within the first few iteration pushing prices up to the competitive fringe's combined heat and power stations. EDF's nuclear plant exerts market power by gradually increasing prices which lead to higher prices during off peak hours. Once EDF-NUC reaches the competitive fringe's coal capacity at a price of 40 pounds, the model stalls briefly before prices have increased enough to convince EDF-NUC to bypass the competitive fringe's coal.

These results have important real world implications even though it is unlikely a generator will ever be able to increase its offer so drastically. Plans to build or increase base load capacity should consider how the merit order will be shift. By moving agents closer to the SMP, increasing base load can empower strategic price behavior. Considering the new intersection between demand and the SMP is relevant beyond strategic behavior. If the intersection coincides with a particularly volatile technology, future prices will also fluctuate.

Phase two: importance of capacity withdrawal in an inundated market

What happens to *Big 6 Price* simulations in the latter parts of decarbonization is that the increase in base load prohibits EDF-NUC's ability to set prices. The total non-disruptive capacity reaches a critical point in 20 years reaching 28,236 megawatts. This is the first time non-disruptive capacity is capable of satisfying any hourly demand period since the lowest demand reaches is low as 27,803. Still the non-disruptive capacity is only capable of covering one period of the day and given nuclear capacities proximity to demand, *Big 6 Price* is able to exploit its position. Increasing decarbonization any further pushes the non-disruptive capacity over more and more demand periods quickly reducing the exploitive potential of nuclear. From Figure XXXIII it is possible to see how in 20 years, the non-disruptive capacity is just beginning to suffice while in 30 years, non-disruptive capacity is capable to supplying all off peak periods.

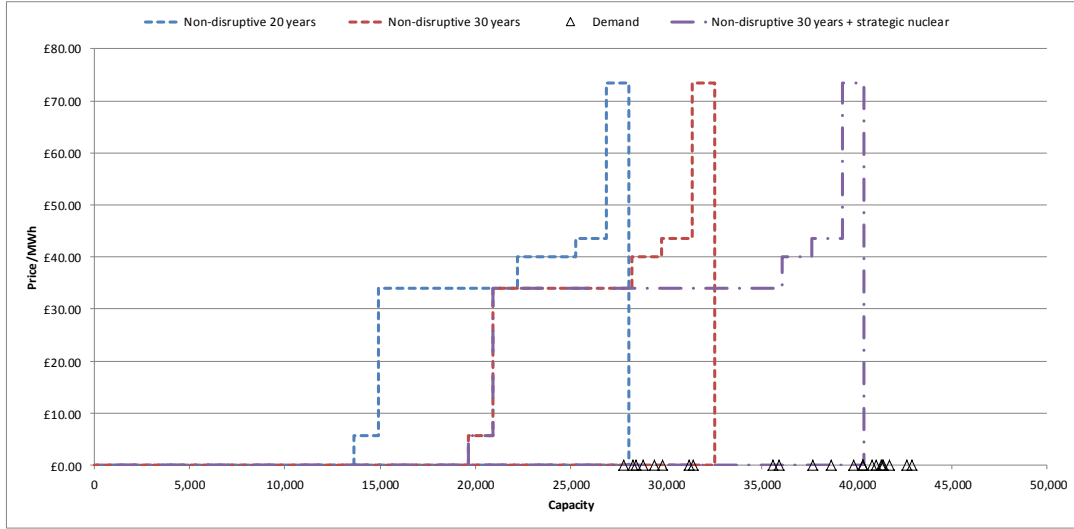


Figure XXXIII

This means nuclear operators are no longer able to bypass the competitive fringe and increase the SMP for off peak hours. Nuclear capacity therefore limits its offers to around that of the competitive fringe's gas. With both nuclear operators providing full capacity at a price around 34 pounds, the non-destructive capacity grows to nearly 40,000 megawatts in 30 years. This does not fully cover demand for all hours of the day but the companies that do not have nuclear facilities will not price themselves out of the merit order. Therefore, less concentrated *Price* simulations converge to near competitive levels in the latter stages of decarbonization.

In 15 years market power for *Nuclear* reaches its lowest level. As counterintuitive as it may be, continuing to substitute wind for coal begins to increase *Nuclear's* ability to distort prices. Two forces are responsible for the non-monotonic price formation in *Nuclear*. First withholding nuclear capacity is made more profitable by the competitive fringe's diminishing ability to hold prices at 40 using coal. The base load supplied by offshore wind pushes gas further and further over demand to make up for the lack of coal. In competitive scenarios this lead to lower prices, but without as much coal at the next price level, withholding capacity is more likely to cause a jump in prices. The lack of coal also allows *Nuclear* to leverage other strategic facilities by lowering total capacity in the market which can push the SMP onto past competitive facilities onto a strategic one which can then exploit the opportunity to set prices. The second force driving prices upwards is the importance of wind plants in each company's portfolio. This facet of decarbonization has not yet been discussed in this section but it may help explain the unexpected varied results both *Nuclear* and *Price* experienced with regards to decarbonization. These facilities open up a new revenue stream that does not have the ability to price itself out of the market and therefore reaps the full reward of any price increase. As winds capacity grows, companies rely less on existing facilities for profit decreasing the

importance of backlash from strategic behavior. Withdrawing almost all nuclear capacity forces the non-disruptive capacity from the purple line in Figure XXXIII back to the red line. Take *20 years* for example. This is the first simulation where *Nuclear* exhibits non-monotonic behavior. Figure XXXIV breaks down the simulation by looking at the merit order stack by iteration.

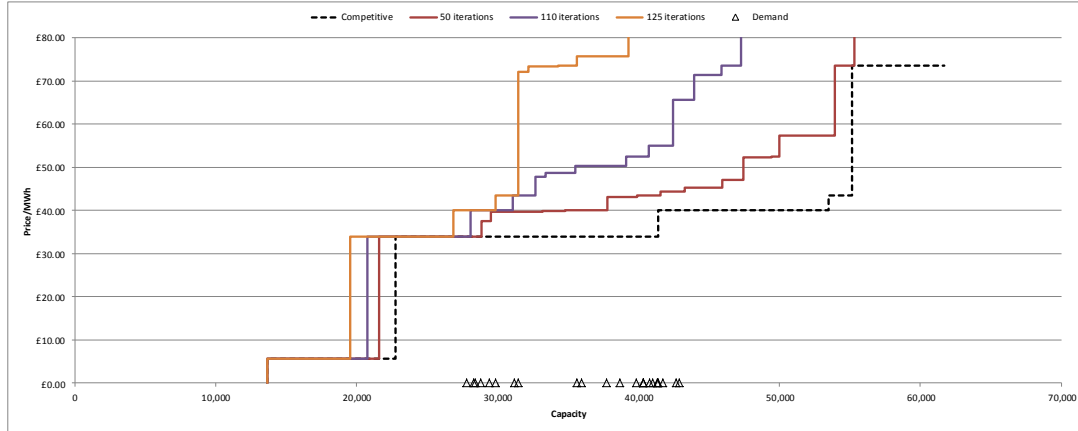


Figure XXXIV

In the first iterations strategic gas plants increase offers to that of the competitive fringe's coal capacity. They are still hampered by an unwillingness to bypass the competitive fringes coal capacity at a price of 40. Simultaneously, strategic coal agents begin to increase prices at during peak demand periods. By withholding capacity the nuclear operators pull the merit order further to the left. This has a twofold effect on the merit order. First, the competitive fringes gas capacity is no longer setting the SMP in off peak hours. Second, the strategic agents at and around the price of coal are able to bypass the competitive fringes with less risk of being excluded in dispatch. What Figure XXXIV illustrates is that the withdrawal of nuclear capacity becomes an important tool in getting past the limits set by the competitive fringe.

In later decarbonization periods such as *30 years*, offshore wind capacity moved the merit order stack so far to the right that it has pushed nuclear capacity over demand in off peak hours. This means nuclear facilities start out as the price setter for off peak hours. This gives them the power to raise prices from 5.6 to 34 for several periods of the day. In *30 years*, there is sufficient gas capacity to cover demand during low hours so prices do not rise above 34 for several hours of the day. *Nuclear* is still effective because as the nuclear facilities withdraw capacity, more and more peak demand intersects the merit order at far enough right to allow strategic gas facilities to exert market power by increasing their offer. Since withdrawal of capacity is continually and sufficiently reinforced the nuclear facilities perpetuate this cycle until nearly all of nuclear capacity is taken out of the market. Taking out such a substantial capacity leaves the market with only the 35,027 of non-disruptive capacity, granting unlimited market power to the remaining strategic operators as long as another operator does not undercut their bid. Note that low

capacity hours are still sufficiently covered by the 35,027. Because peak hours require more capacity, strategic agents can more easily exert market power during these periods of the day. Market power is measured by taking average daily prices therefore divergence limited to peak hours still cause market power to increase.

Comparing the two strategies, the later years of decarbonization limit *Prices* exploitive capacity because the increasing base load prevents nuclear from setting the SMP during off peak hours. Since the risk of losing dispatch is too much for these operators both strategic nuclear plants flood the market with capacity. *Nuclear* simulations garner increasing market power primarily due to the diminished coal capacity of the competitive fringe. Capacity withholding is essential in later decarbonization periods because the non-disruptive capacity is capable of producing enough output to cover low demand periods. The later years of decarbonization make it impossible for prices to increase above 80 pounds for off peak hours. Capacity withholding is still effective in transferring market power over peak demand periods to strategic gas and the remaining strategic coal. *Nuclear's* superiority continues until total decarbonization.

Phase three: convergence in 40 years

The return to near competitive levels in *40 years* initially comes as a surprise given the market power generated by strategic behavior in all other market settings. The merit order stack, however, provides a reasonably clean cut answer to this sudden collapse. **Error! Reference source not found.** shows that even or *Big 1* market settings, neither *Price* nor *Nuclear* are capable of escaping the limitations produced by *40 years*.

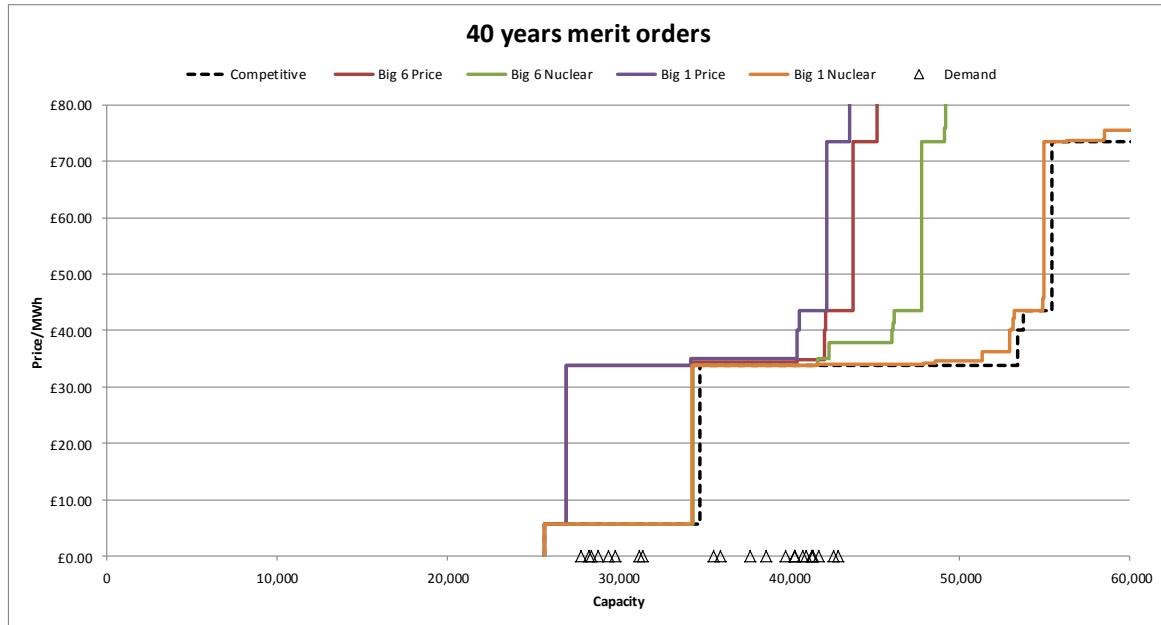


Figure XXXV

In *40 years* the increase in offshore wind has pushed the merit order stack so far to the right that in competitive setting nuclear plants are the last dispatching facilities for off peak periods. By *40 years* the total real capacity generated by such technologies reaches 19,351 megawatts. The competitive fringe's nuclear and gas plants increase the total to 34,219. This means that in 40 years as long as no wind capacity is withdrawn prices will be at 34 or below for demand less than 34,219 megawatts. The SMP during low demand hours will never rise above 34. Including the more expensive competitive fringe technology brings the total real capacity to 37,291 megawatts. This is enough capacity to cover several peak periods of demand.

Capacity withholding of nuclear could only generate increased profits if every strategic player significantly increased all bids for all plants operating on gas or coal. Even so, a large quantity of nuclear would have to be withdrawn from the market before the competitive fringe can be bypassed. The highest demand ever reaches is 42,884. Combined with the competitive fringe and other non-disruptive capacity, nuclear produces 45,159. Prices would therefore only diverge if 2,265 megawatts of nuclear were withdrawn. The same market power limited influence of *40 years* is visible in all possible strategy and consolidation variations.

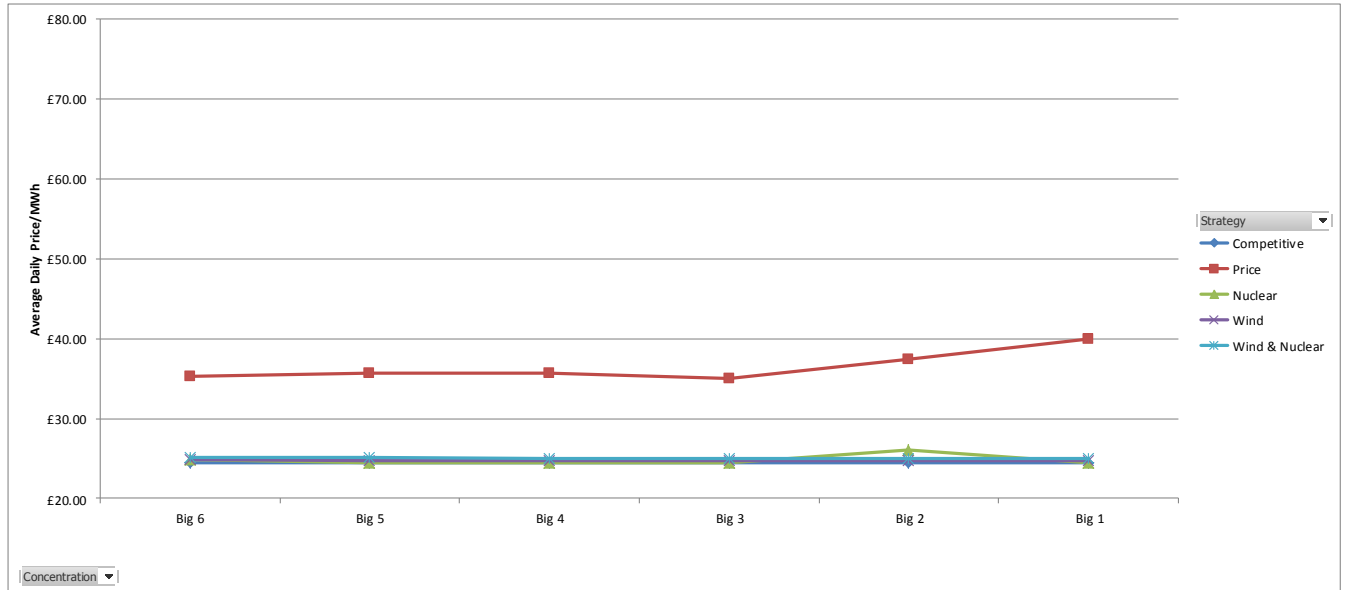


Figure XXXVI

Only in *Price* are companies able to significantly distort the market. The can quickly be understood by looking at the last dispatching plant information. What has happened is the two nuclear facilities have essentially prices themselves out of the merit order stack which was propagated by the fact that nuclear facilities set the SMP in off peak hours. In *Big 6 - 3* prices increase until they hit gas the gas capacity which is offered competitively at 34. Average daily prices are slightly higher than 34 because during peak hours, gas capacity is required above that offered by the competitive fringe and strategic gas plants can cause a slight increase. In the more consolidated markets of *Big 2 - 1* the remaining players achieve a slight premium over less concentrated markets by uniformly increasing offers for gas plants resulting in the combined heat and power stations dispatching in the highest peak period.

The applicability of this particular result is limited due to the extreme market conditions in place. There is no conceivable reason to believe that an electricity market will be able to provide over 25,000 megawatts of capacity at a price of zero. It is possible, however, take out all the capacity with negative marginal costs and simply decrease demand by the same amount. In this way, the *40 years* simulations tell us how a far smaller market might be affected by strategic behavior. Descriptively in the market there is only one strategic technology currently used in dispatch (nuclear offered at 5.6 pounds), the next most expensive technology (gas offered at 33.9 pounds) has sufficient competitive capacity that strategic behavior is impossible without the cheaper technology withdrawing substantial amount of capacity. What we can infer with this simplified interpretation is that for the two nuclear plants, price bidding is a reasonably simple means of increasing prices to the price of the more expensive technology. Capacity withholding on the other hand is difficult to justify because such a large amount of capacity must be taken out before the strategic gas

can at all influence prices. Therefore, a regulator in this particular market would be well advised to monitor the price offerings of the cheaper technologies rather than the capacity behavior of the large nuclear operators. Effective capacity withdrawal would be obvious to spot and regulate given quantities involved.

The *Price* data in *Year 40* simulations show that there is an inherent opportunity to increase prices with such a large gap in prices. There are offers between the price of nuclear and gas. In a competitive scenario these two technologies differ by 28 pounds. This large cap creates an opportunity for nuclear operators to increase prices at least up to the price of gas. Discrete price jumps in the merit order can be harmful even if the market has enough competitive capacity to satisfy demand at any level.

Discussion

Summary of notable findings

The results and analysis underscore the complexity of the relationship between market structure and market power. None of the generalized expectations regarding market structure inputs held up against every outcome of the model. Furthermore, capacity withholding does have its merits when it comes to exploiting market power but the outcome depends heavily on market conditions. The considerable variation in the data and the fact that results do not conform to expectations is a testament to the functionality of the model itself. To some extent the most profound implications are derived from simulations where prices do not diverge rather than those that do. Also, the comparison of *Price* and *Nuclear* simulations provide information applicable to empirical markets as well as future studies using agent based simulation in a similar setting. How the model applies strategic capacity withholding and which settings provide optimal conditions for capacity withdrawal is important in our understanding of the applications and limitations of agent based simulations. For policy makers and regulators the results highlight the importance of the complex relationship between the merit order stack and strategic behavior. Market power in the uniform price auction of a liberalized electricity markets does not adhere to a strict set of rules. The data shows that market power can be bolstered by a development thought to be benign. Likewise, an intervention aimed at mitigating market power may well have a perverse effect. Even a colloquialism like “competition increases efficiency” does not hold for all market conditions. Clearly some of the results are misleading due to inherent flaws in the model. The company profit function is not sophisticated enough to account for a fully realistic decision process. This flaw cripples both *Wind* and *Wind & Nuclear* simulations due to the symmetry of both the algorithms. Nevertheless results from *Price* and *Nuclear* can be justified and analysis of the data has several compelling implications.

The relative strength of *Price* simulations comes down to the market power garnered by nuclear plants when it comes to setting the SMP for low demand hours. Without sufficient non-disruptive capacity the market is at the mercy of nuclear operators. They quickly realize and exploit their position due to their large size and the lack of competition in the merit order at their price level. Capacity withholding in *Nuclear* is effective in a market with large discrete jumps in the merit order. If there is not a significant rise in price, the opportunity cost is too high given the profit margin and large capacity generated by nuclear facilities. In a market inundated with capacity, market power may necessitate some withdrawal before other agents are able to exploit their position at and around the SMP. In these market conditions, nuclear capacity withholding proved to be an effective market power catalyst. For both *Price* and *Nuclear* simulations the behavior of EDF’s one large nuclear plant is instrumental in analyzing market power.

With regards to consolidation, the story is not consistent for *Price* versus *Nuclear* simulations. The two strategies yield idiosyncratic deviations from expectations but the *Nuclear* data is far more robust. In *Big 3* and *Big 2* settings, market power is reduced to near competitive levels. In this market structure, acquisitions prohibit agents from realizing market power by creating a merit order stack devoid of any significant price differentiation. There are still discrete price increases when moving from one technology to another but the infra marginal generation never generates enough price differentiation to warrant capacity withdrawal. *Nuclear* is most effective when a nuclear agent is able to gradually realize returns for their behavior. An operator will only withhold a limited quantity at a time so price differentiation is needed to reinforce the behavior.

Price's response to consolidation is less surprising than that of *Nuclear* simulations. For the most, part average daily prices increase with consolidation. Still a few simulations prove to be inversely effected by consolidative activity. Acquisitions may limit market power if and when competition between two agents promotes price differentiation. The asymmetric information dispersal in less concentrated markets creates is more likely to create a segregated merit order which is vital to the creation of market power in some settings. Assigning two plants with similar cost structures to the same company produces results where the agent will either increase the price offer for both facilities or neither of them. This means the price gap between the two will never be significant enough to encourage one facility to increase prices. *Price* and *Nuclear*'s inverted response to consolidation are linked through the importance of price differentiation in promoting market power. The difference between the two strategies lies in how the differentiation is created and how strategic behavior is able to capitalize on the opportunity. The results are more pronounced in *Nuclear* because the impact of capacity withholding hinges on price discrimination. Again price differentiation is so vital to capacity strategies because extended flat cross sections in the merit order prevent short term reinforcement. Without direct support the strategic agent never withholds out more than a limited portion of its total capacity. To control market power based on capacity withholding, the relationship between capacity withdrawal and differentiated price offers has be to addressed in concord with an investigation of the other assets owned by the company. A motivating factor behind EDF-NUC's withdrawal of capacity is the inclusion of other company assets higher in the merit order. A regulator may have a hard time identifying strategic capacity withholding by only looking at the marginal increase in SMP. The short term impact may neglect the shift in market power. By gradually phasing out capacity, nuclear generators catalyze strategic behavior around the SMP.

The factors leading to the non-monotonic results in decarbonization share some of the same influences as those that effect consolidation. To reiterate; contrary to expectations the price formations of both *Price* and *Nuclear* simulations do not decrease monotonically with increasing levels of

decarbonization. Less concentrated *Price* simulations take advantage of the increasing proximity nuclear plants have to demand in the merit order stack. For the same *Nuclear* simulations, early levels of decarbonization limit market power because the competitive fringe has enough coal capacity to depress strategic behavior and the cheap wind capacity increases base load. This trend reverses for both strategies in the latter years of decarbonization. The inversion occurs roughly when the total non-destructive capacity in the merit order starts satisfying off peak demand hours. This development coincides with diminishing cross section in the merit order at a price of 40 pounds generated by the competitive fringe's coal facilities. Strategic coal and gas agents find it easier to bypass the limitations in the merit order at a price of 40 and achieve a greater degree of price differentiation. This in turn propagates nuclear capacity withdrawal. In *Price* simulations prices begin to decrease in the latter years of decarbonization because there is enough base load to satisfy off peak demand. Nuclear operators will not price themselves out of the market in off peak hours making them impotent to increase prices. These findings are relevant to several aspects of the greater discussion of market power and market structure. For one introducing a cheaper technology to the market does not necessitate lower prices if market power is present. Strategic agents are quicker to realize and exploit their position when closer to the SMP. Also the results from *Nuclear* again stress the importance of price differentiation in the merit order when it comes to strategic capacity behavior. By taking out the marginally expensive, decarbonization enables price differentiation by empowering strategic agents around the SMP in peak hours that have less capacity to discourage strategic price increases.

Policy implications

Reducing market power has to start with a fundamental understanding of the processes and opportunities inherent to the problem before any action is taken. Putting the analysis together creates a checkered tapestry of market settings with no consistent message when it comes to the presence of market power. The same policy development or policy measures that increase the efficiency of the market in one setting can reduce efficiency in another. Also the improperly predicting the decision process of a generator can lead to misplaced policy measures. Still the data is no randomly distributed and the analysis produces guidelines for where to look for market manipulation rather than where to find it.

The degree of differentiation in the merit order stack's price is essential to any manipulative behavior. Capacity withholding is not profitable if demand intersects the merit order at the same flat cross section. Differentiation is key to the price algorithm because the marginal differences between two offers represents how much the lower offer can increase its price before excluding itself from the merit order. The surprising consolidation results for *Price* and *Nuclear* show how similar price offers can prohibit strategic price behavior at and around the margin. To a regulator, the behavior RWE's in *Nuclear* simulations is evidence that certain acquisitions should be encouraged when one company is particularly aggressive. The

acquisition of RWE by EDF indicated that consolidation can improve the efficiency of a market if it reduces price differentiation. To reduce market power a policy maker may want to impose limited price differentiation by using discrete preset offer levels. In this system instead of granting complete flexibility when it comes to the price of an offer, generators would be obligated to put each offer in a price bin. Companies would have to take a large risk when increasing its offer from one bin to another compared to the risk they face when slight increases are allowed. Assuming no collusion is present in the market, the likelihood two or more generators will simultaneously jump from one bin to another is slim. This reduces the chance that enough capacity is removed from the bin setting the SMP to warrant an increase to the next bin level. In the model, companies are able to slowly increase price offers until they reach the next plant in the merit order stack at which point they may reduce their offer. Prices continue to increase because by crossing pricing itself out of the SMP, the plant transfers market power to the plant that they bypassed. When the newly empowered plant begins to increase its price the process is perpetuated because the first plant only reduces its offer to that of the last iteration. Obviously the size of the bins would be essential to the efficiency of the system. Only including a few bin sizes would erase the fail to represent the true cost of production. Too many bins would defeat their purpose altogether. Lastly, policy makers would have to decide how to optimally allocate dispatch within each bin.

Another way to prevent disruptions caused by price differentiation is through the use of buffer capacity around the SMP. A policy maker or regulator could build up the buffer in several different ways. They could provide incentives for investment in generators with a cost of production around the SMP. More competition around the SMP is likely to discourage manipulation but it is no guarantee of efficiency. An expensive but effective alternative would be for the regulator to take control or purchase their own generation facilities that they can use to fill any gap in the merit order. To do so however, the facility would have to have sufficient dormant capacity that it is able to cover demand when a manipulative actuation requires its dispatch. Getting a government entity or regulator involved in generation is basically un-liberalizing your market. Moreover from a pure liberalist's point of view, the market will still be efficient because new investment in production will fill in the gaps created by the strategic behavior. If a market is able to achieve above normal profits new entrants will inevitably join them. It is not quite so simple in an electricity market because there are large barriers to entry. To begin, there is a large lag time between the investment and the date the plant is operational. Also it is difficult to accurately predict future prices and the incumbents may force out the new entrant by reverting back to competitive levels.

Close monitoring by a regulator who has enforcement capabilities is the simplest solution that does not compromise the core values of liberalization. Empirically even the most liberalized markets still have significant oversight. The electricity industry is so essential to a region or country's livelihood that the letting

the market go unchecked could spell disaster. There is a happy balance between too much and too little oversight. In markets with poor corporate governance, an attempt to liberalize the electricity sector may want to consider a partial liberalization. An integral part of liberalization is new investment in the sector. Because infrastructure has a long lag time, the transition to a free market should be gradual. For example regulators could require a firm to rigorously justify any change in price offer. Capacity withholding is easier to disguise as maintenance or something of the sort. To combat withdrawal disguised as maintenance, officials can implement preset mandatory maintenance periods where the plant is required to exclude at least some capacity and take care of upkeep. The regulator could assign the maintenance in periods where the capacity is not essential to maintaining price levels. Some technologies like wind are inherently linked to variable capacity offers even with no strategic behavior. Strategic capacity withdrawal is even harder to pinpoint for such technologies and a more comprehensive policy is needed.

Implications for the UK and Wales

The results of these simulations should not be used as a guideline for possible real world outcomes in the UK and Wales electricity sector. On the other hand, because the model draws on data from this region any conclusions that can be extrapolated from the results are particularly applicable to this market. For regulators, EDF's nuclear plant is consistently at the forefront of market manipulation. Its size and low starting point in the merit order stack makes it uniquely capable of increasing the SMP in off peak hours. To remove EDF's power regulators can set a limit to how much price offers can increase in a given period. Price wise, both nuclear operators are so much lower than the next most expensive technology that limiting nuclear facilities to a 500 percent increase would still prevent them from bypassing gas. In this way, *Price* simulations that rely heavily on EDF's nuclear facility to increase prices are quite unrealistic. A regulator would not have a hard time diagnosing the problem and there is little chance that EDF could justify such a massive increase in prices. The same plant plays a critical role in *Nuclear* simulations. Here the results are more realistic. In some simulations EDF can trigger divergence by taking out even a little bit of capacity. To discourage EDF from strategically reducing capacity, regulators may want to evaluate the relationship between intercompany profits. We have already discussed how price differentiation promotes market power the increase in prices alone is normally not enough to encourage further withholding of capacity by EDF. Instead the company typically withholds capacity when it generates a jump in prices while simultaneously including its coal and gas facility in more dispatch periods. If EDF begins to manipulate the market using its nuclear firm to bolster its other technologies at and around the SMP, regulators should consider forcing a divestiture.

The plans to bolster renewable energy production in UK and Wales can make use of several of the findings in this study. Unfortunately, the data from wind capacity withholding proved to be inconsequential,

but suggestions from the other simulations are applicable. After all; the code only distinguishes a facility by cost of production. Renewables like wind and solar are naturally variable. Wind is especially hard to predict. The model does not properly account for this variability; instead it assigns a seasonal coefficient to total capacity. How the lower predictability will affect the market comes down to where the technology lands in the merit order stack. If the government heavily subsidizes investment in renewables, the merit order will be pulled back and forth with winds variation. This variation will lead to more push and pull around the SMP which could encourage or discourage market power. On one hand, variability in base load could reward price differentiation in a similar way to nuclear capacity withholding. Contrastingly using intermittent renewables as base load will lower the reliability of information generated by plants around the SMP. What this means is that it will be harder to distinguish between an increase in profitability caused by an increase in price and an increase in profitability caused by a low renewables output. Making information dispersal unreliable will decrease the exploitive opportunity if agents are not willing to gamble by increasing offers. *Nuclear* simulations point out the importance of the relationships between a company's assets and capacity withdrawal. If renewables constitute a large portion of a company's portfolio, they may be able to capitalize on the variable output by pricing other assets high when then know conditions are bad. Also with regards to renewables; government subsidies and emission rights lead to high profit margins. Higher profit margins cause the opportunity cost of dormant capacity to increase. This in turn leads to reluctance on the part of generator when it comes to withholding capacity. This effect may have been overstated due to the symmetry of the two algorithms. Still profit margins have a special link in uniform price auctions since every participant receives the SMP. Therefore regulators concerned with market power may want to consider the implications of any future increase or reduction in subsidies. The inverse can be said for penalization of carbon emitting technologies. Faced with decreased profitability a strategic firm may be sufficiently motivated to abandon the capacity all together or price itself out of the dispatching merit order to force prices upwards.

The UK and Wales market should also recognize the central role the competitive fringe plays in limiting market power. To an extent the simplified marginal cost assumptions in the model are responsible for the unusually flat cross sections in the merit order. Still the presence of some capacity that will always offer at a competitive marginal cost is a powerful tool in preventing market power. A larger company can play the same role in reducing market power as long as their offers remain consistent. Significant market power is attained when several strategic agents work in what almost appears to be implicitly collusive. Of course the model does not allow collusion and what is happening is the strategic agents are maximizing their own profits. If only one or two of the big six companies were strategic the price results would certainly be much lower. The combined market power of all six operators is far greater than that of any single company. Regulators may therefore want to encourage consistent behavior or price offers. If a nominal reward

discourages the strategic behavior of even one of the big six companies it would have a profound effect on the market power of the remaining five companies.

External validity

The beauty of this model lies in its flexibility in the interpretation and emulation of empirical conditions. Apart from availability rates, the differences between technologies is boiled down to a single exogenous variable; marginal cost. The last section highlights this feature of the model by showing how developments in the UK and Wales power market contrary to the projections can have a similar impact when it comes to market power. Taking this discussion one step further; by creating a simplified and flexible mechanism for diagnosing market power, the results of the model might be relevant to markets other than UK and Wales. For example, the increase or decrease in market power due to decarbonization efforts in the UK and Wales power market where offshore wind is subsidized may contain the same catalyzing factors as the emergence of cheap natural gas in the United States. That is not to say that this is likely. The US power market is undoubtedly dissimilar to that of the UK and Wales for several reasons including unique policies when it comes to liberalization. Yet, these two scenarios may have a connection when it comes to market power. It is possible to argue that in both cases, the merit order stack loses capacity at higher offer prices and gains capacity at lower levels. Weather market power is mitigated or strengthened depends on the interaction between each market players strategic behavior and the merit order stack. In this way, the conclusions of this analysis may have relevance for decision makers in other markets.

In any uniform price auction, a simple way to diagnose market power is by calculating the non-disruptive capacity at various price levels. These calculations can be repeated many times depending on what is labeled non-disruptive. For example, in several simulations both strategic nuclear facilities are labeled non-disruptive because the data shows a refusal on their part to price themselves out of dispatch even in low hours. If a market has insufficient non-disruptive capacity the only thing limiting divergence is the companies' ability to realize and fully exploit their position. Comparing non-disruptive capacity calculations to demand figures indicates a range for strategic behavior. The range is infinite if the definition of non-disruptive is narrow enough to create a gap between demand and the non-disruptive merit order.

Possible failures

Symmetry

Symmetry in the capacity and price algorithms can prevent the model from functioning properly. Both algorithms are based on company profits. Strategic behavior may decrease profits in both algorithms by either bumping capacity out of the merit order or by reducing dispatched capacity in the case of price

and capacity bids respectively. The strategic behavior of all generators in a company's portfolio will stall if the behavior of one plant consistently and significantly decreases company overall profits. Consider a situation with one strategic market participant with two plants; one base load acting on capacity and one that dispatches only in peak periods and plays on price. All other capacity in the market acts competitively. It may be the case that decreasing capacity of the base load provider leads to a new, more expensive technology being the price setter. All else equal, the company's profit would increase when the base load capacity is withheld and the algorithm would reinforce and perpetuate this behavior. This cycle, however, may be disrupted by the company's other plant playing on price. When the company's profit increases, this plant's next offer will be at a higher price. This action could lead to the plant being pushed out of the merit order such that it does not dispatch even in peak period. If downwards pressure on profits caused by this plant is enough to offset the upwards pressure on profits generated by the first facility, both algorithms will bounce back and forth between the last offer and a new higher one. The *Wind* simulations demonstrate how symmetry is particularly harmful if a highly profitable base load generator is the capacity algorithm.

The model attempts to deal with this problem by instituting randomly distributed numbers centered at 1 to both algorithms. This addition disrupts the symmetry inherent in the algorithms by varying the scale of each decision a strategic plant makes. The variation is able to cope with symmetry unless the profit contribution of one plant eclipses the contributions of the company's other assets. The symmetry of the algorithms also prohibits certain forms of sequential behavior. In the previous example, the peak load plant may not be at risk of being bumped out of the merit order once the base load facility has withdrawn a certain amount of output and production has shifted to a more expensive technology. If this was the case, it is feasible that the model does not account for the possibility of the company delaying the strategic behavior of the second plant until market conditions are optimal. The symmetry of the offers in the model's bidding process is not isolated to plants operating on price versus capacity algorithms. The same logic may be applied to plants using the same strategy. This scenario is, however, much less likely and would require a number of conditions to be satisfied.

Certain applications of symmetry are justifiable. It is reasonable to expect that two plants using the same technology owned by the same company will be symmetric. This healthy function of symmetry is a driving force behind the unanticipated consolidation results. The limitations of wind capacity withholding are therefore a symptom of unrealistic parameters. The heavy subsidies are reasonable in the current market setting, but it is irrational to assume the almost 25,000 megawatts of wind capacity in *40 years* can be offered at the same negative price levels. In hindsight adding code that adjusts wind's production cost along with decarbonization could have at least reduced the scale of the problem. Keeping wind's marginal cost below zero did, however, ensure that decarbonization leads to increasing base load. This would be a new

problem because if wind had a positive marginal cost, strategic wind facilities would be able to price themselves out of the market. It is already a stretch to allow nuclear operators to increase price offers so markedly. So this failure in predictive foresight does yield some advantages in the end.

Trigger problem

Simulations with a sustained increase in prices end up clearing out the merit order of all strategic capacity at any reasonable price level. Because no information is shared about the market or competing offers, companies have a hard time distinguishing the impact of their own strategic behavior from that of another agent. An upwards trend in prices trigger a response by all strategic agents as long as profits are increasing. The more agents that are triggered, the more likely prices are to increase and vice versa. This snowball effect promotes market power by continually shifting all strategic capacity in merit order. In the *Big 1* consolidation setting, this development is referred to as momentum. Trigger is slightly different in that it several companies are involved. Manipulative behavior is a prerequisite to the trigger effect so its presence does not contradict existence of market power. The problem is that the number of iterations required to generate a full blown trigger effect is arbitrary. Market settings are often conducive to triggering and consolidation makes reduces the number of players. Even so results can overstate market power due to chance synchronization within the allotted 200 iterations. At the same time another simulation under similar pretenses could fail to trigger the same response. The marginal difference in market structure or strategic behavior could be irrelevant beyond the fact that 200 iterations happened to trigger all of the strategic companies. The possibility and potential of triggering is strengthened by the fact that the algorithms can only go back to the offer in the last iteration if the strategic behavior has become unprofitable. If profits cause the offer to increase twice in a row, the model will not let the agent revert back to the initial offer. In the data this means the market behavior is more likely to be overstated than understated.

The trigger problem underlines the importance of disciplined and thorough qualitative analysis. The same can be said for symmetry. Running numerous simulations builds up the robustness of the results but there is always the chance that the analysis does not properly identify the root of the market power in the model. Reading the output at the end of the model is like looking at a broken windshield. There are so many fractures and broken pieces that pinpointing the point of impact can be difficult. Lines in the glass will trace back towards a central area but there things are chaotic with tons of little pieces. Furthermore, there may be two points of impact that combine to create a structural weakness in the merit order. This all comes back to the qualitative nature of the study rather. A quantitative diagnosis is certain to overestimate the presence of market power. The important conclusions are found in qualitative descriptions of the model based on sound assumptions.

Problems with fixed marginal cost

The marginal cost of production is held constant for every plant using the same technology. While there is a strong relationship between marginal cost and technology, the reality is that marginal cost depends also on a myriad of other factors. These factors may both create differences among plants using the same technology and change a plant's marginal cost over time. For example, a small coal plant using machinery from ten years ago may have a significantly higher marginal cost than a large new coal plant put into operation just a year ago. Additionally, both plants' marginal cost may change over time depending on the cost of coal. The model also applies only eleven technological categories. This fails to consider the significant differences within each category. Continuing the example of the two coal-fired plants, over the past century there have been vast improvements in the efficiencies of coal plants. Newer facilities using supercritical integrated gasification combined cycle machinery are able to extract more of the chemical energy in coal with efficiency rates above 50%. In stark contrast, the average efficiency of global coal power plants is around 34% (Tomczak, 2012).

The differences in the two coal power plants highlight the importance of the learning curve in setting the price of production. The learning curve of a technology used in energy production relates to improvements in cost and production efficiency. Technologies such as coal that have been around for a while are considered to be further along the learning curve. This observation implies we are unlikely to see improvements that substantially increase the efficiency of coal-fired plants above that of a supercritical power station. Newer technologies find themselves lower on the learning curve and over time we expect to see sizable cost and efficiency improvements. Renewables like wind and solar power are widely considered to be early along the learning curve. Forecasting marginal cost developments can be unreliable since the learning curve is more of a rule of thumb than a guaranteed model. In the case of renewable, government subsidies play a major role and any prediction must take into consideration policy changes.

The combined effect of increasingly differentiated and complex marginal cost curves would be a more differentiated merit order stack than that produced by the model. Price differentiation consistently proves to be critical in the formation of market power. The purpose of the model is to present an extreme idealized scenario where the impact of strategic behavior on market power is identifiable. By allowing cost calculations to differ by plant, this relationship may become indistinguishable from the influence of changing marginal costs. The competitive merit order stack is clearly an oversimplification of reality. Using realistic cost functions would make the data difficult to analyze.

Conclusion

Agent based simulation has the potential to take some of the risk out of the process of liberalizing an electricity market. The inherent complexity of strategic behavior's impact on a uniform price auction makes it difficult to fully consider the market power garnered by a profit maximizing firm. The failures of numerous electricity market liberalizations highlight this point. Market power is not always the problem but creating a more free market is not a guarantee of more efficiency. There is still a huge opportunity to achieve higher efficiency through liberalization like so many other economic topics there is seldom a one size fits all solution. Handing the industry over to profit maximizing institutions is problematic if firms are able to use strategic behavior to manipulate prices and generate abnormal returns. This problem is particularly harmful to electricity markets because of high barriers to entry and demand inelasticity. A sophisticated understanding of the potential disturbances produced by market power will help increase the efficiency of new and existing liberalized markets by promoting appropriate policy measures. Models like the one used here increase this understanding. The programmability of market structure inputs makes simulation a flexible tool. This study adds to the field by introducing capacity withholding strategies to an established model. Including the second behavioral algorithm improves the applicability of the model because the price algorithm alone does not fully encompass the tools at an agent's disposal. The results show that adding capacity withholding does indeed make a difference. When the behavior of the agents is qualitatively justifiable the results frequently contradict expectations with important implications for policy makers and regulators. The investigation of the failures of the model underscore the limitations of quantitative conclusions based on agent based simulation.

The level of price differentiation in the merit order is absolutely critical to the formation of market power in a uniform price auction assuming no information dissipation. Flat cross sections in the merit order stack limit the effectiveness of both strategic behaviors by lowering the probability of any movement in price. Without any movement in price, manipulative behavior is not reinforced and the strategic agents do not realize their full market potential. The importance of price differentiation implies that increasing the size of a firm can have a perverse effect on its market power. Generators owned by the same company are more likely to have similar production costs which will lead to flatter cross sections in the merit order. For policy makers this means promoting competition can in fact reduce efficiency. They should therefore closely consider the effect a policy will have on price differentiation if market power is a potential problem. The decarbonization results highlight how important it is for policy makers to plan out and consider how investment in generation will influence market power. Adding cheap base load capacity can actually increase prices if it increases the chance that a strategic agent will discover market.

Knowing what market settings lead to a comparative advantage of the capacity algorithm over price behavior can help regulators identify the possible manipulations their particular market setting is conducive to. Capacity withdrawal is symptomatic of a market that is inundated with capacity. Also a generator that is responsible for a large share of corporate profits is better suited to withhold capacity if they cannot influence prices without excluding themselves from dispatch. Still taking capacity out of the market is only effective if there is sufficient price differentiation around the SMP.

The tradeoff between liberalization and market power depends on the particular setting. On one hand liberalization should result in more efficient allocation of capital and prices that accurately reflect the cost of production. On the other a liberalized market is never completely efficient. Market power is one of many potential inefficiencies. The decision to liberalize has to be met with the realization that some degree of regulation is typically required. There is no way to predict the specific developments of liberalization with any certainty but a regulator may have to help the process by promoting investment or intervene in some other way. If market power is a problem, the model has shown that best policy measure to reduce its impact is not necessarily break up big companies or to make sure enough capital is put towards new capacity. The policy has to consider its impact on the merit order position of the companies manipulating the market and how the new market structure alters each firm's decision process.

In reality it is not nearly as clear cut to differentiate intentional manipulation from the natural variation in offers. A company may disguise a strategic withdrawal of capacity as malfunction or take a larger profit margin by intentionally overestimating its costs. The harder it is to separate strategic behavior from honest variation, the more time and money will have to be spent on regulation. To reduce dependence on fossil fuels electricity markets will have to shift production to less established technologies several of which are based on unpredictable factors. This will make it harder for regulators to make the distinction between natural and manipulative behavior. Applying agent based modeling to the study of strategic firm behavior can help regulators identify and diagnose market power without increasing more regulation. As a field of study, agent based simulation can help develop an understanding of what policy decisions promote efficiency. Without a revolutionary technological development in generation, the efficiency of markets will be critical to how the world copes with its growing energy problem.

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